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Abstract

This paper investigates the effect of R&D on productivity at the micro, meso and macro level. Several meta-analyses were performed to analyse the variation in output elasticities of R&D, based on 1214 observations from 38 studies. Study characteristics explain variations in output elasticities to a large extent. Several results of the meta-analyses are difficult to interpret from a theoretical or an analytical perspective. This can be attributed to residual heterogeneity between studies for which direct causes are not easy to be designated.

Despite the partly unclear results, various conclusions can be drawn with respect to the influence of study characteristics on the estimation results for output elasticities. For example, 1) the output elasticity of domestic R&D at the macro level is (on average) much higher in G7 countries than in non-G7 countries, 2) including human capital as a production factor in the regression equation has a substantial negative effect on the estimated output elasticity of domestic R&D and 3) in high tech industries the output elasticities are substantially higher than in low tech industries.

Furthermore, the results of the meta-analyses made it possible to calculate ‘best guess’ estimates for the output elasticities of domestic private and public R&D capital at the macro level. For domestic business R&D capital the ‘best guess’ estimate amounts to 0.06 for non-G7 countries. For domestic public R&D capital the ‘best guess’ of the output elasticity in non-G7 countries is 0.03. However, the latter estimate should be interpreted with caution, because the effect of public R&D has been investigated in only a small number of studies, with diverging results. The meta-analyses also indicate an important influence of spillovers from foreign R&D capital on productivity. For non-G7 countries the output elasticity of foreign private R&D capital is estimated to be substantially higher than the output elasticity of domestic private R&D capital.

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1. Introduction

Research and Development (R&D) is a major factor in product and process innovation, and innovation in turn is one of the main drivers of productivity growth. Positive external effects may warrant government investments or subsidies. If the government or a firm invests in R&D, it is important to know how large the effects on productivity are. These effects have been estimated in many studies, usually showing positive effects (Hall et al., 2009). However, these effects strongly diverge in size.

This paper contributes to the literature by explaining the variation in results through meta-analyses of existing studies. A database of study results and study characteristics has been constructed, containing 1214 output elasticities of R&D from 38 studies. The output elasticities generally refer to the effect of R&D capital on output, but sometimes R&D expenditure is the explanatory factor. R&D capital is the accumulation of R&D expenditures, adjusted for depreciation due to obsolescence of knowledge.

In the meta-analyses a key distinction is made between micro level, meso level and macro level studies. In micro level studies the effect of R&D is estimated on the output of individual firms. Meso level studies provide estimates of the effect of R&D on the output in individual industries. Macro level studies focus on the effect of R&D on the output at the aggregate country level. Other main characteristics of studies that are taken into account in the meta-analyses are the econometric method used and the specification of the estimated equations. The output variable used as dependent variable (e.g. value added), the definition of the R&D input variable and the depreciation rate for R&D capital are included in the meta-analyses. Other explanatory features are a distinction between low, medium and high tech sectors, inclusion of human capital in the regression, correction of production factors for R&D inputs and constant or non-constant returns to scale in production. In most studies used the effect of business R&D is measured. Estimates of the effect of public R&D are scarce and limited to a few macro studies.

Many studies contain direct output elasticities of R&D carried out in the firm, industry of country itself and output elasticities of R&D carried out in other firms, sectors or countries. The latter elasticities measure spillover effects from outside R&D. In this paper separate meta-analyses are presented for own R&D elasticities and outside R&D (spillover) elasticities. For own R&D elasticities results are presented at the micro, meso and macro levels separately, and for the three levels together. This is based on 827 observations. For outside R&D the number of observations is much smaller: 387. Therefore, the part of the analyses with respect to outside R&D is carried out only at the three levels together.

The meta-regressions show that a substantial part of the differences in results between studies can be explained by study characteristics. For example, including human capital as explanatory variable in regression equations reduces output elasticities of R&D. Assuming ‘optimal’ study characteristics, the meta-regressions are used to compute ‘best guess’ estimates of the output elasticities of business R&D capital and public R&D capital in non-G7 countries. For domestic business R&D capital the best guess output elasticity is 0.06. For domestic public R&D capital a best guess output elasticity of roughly 0.03 can be derived, but this result is subject to much uncertainty because of diverging results in the underlying studies.

Section 2 of this paper describes the studies used in the meta-analyses. The methodology of the meta-analyses is described in Section 3, including the data collection procedure, the specification of the meta-regressions and the variables used. Section 4 presents a test for publication selection. In Section 5 meta-analyses are carried out for output elasticities of own R&D, followed by a meta-analysis for output elasticities of outside R&D in Section 6. In Section 7 ‘best guess’ estimates for the output elasticities of domestic private and public R&D capital are calculated, on the basis of some generally preferable study characteristics. Finally, Section 8 presents conclusions.

2. Studies used in the meta-analyses

As a first step, survey papers were used to find relevant literature on quantitative effects of R&D on productivity (Hall, Mairesse and Mohnen, 2009; Cincera and van Pottelsberghe de la Potterie, 2001; Mohnen, 1996; Nadiri, 1993). This yielded many studies on the micro and the macro level and a lower number of meso level studies. Macro level studies are often relatively recent, because many of these are based on the framework developed by Coe and Helpman (1995). Also, a Google Scholar search was performed using the keywords ''R&D'', ''R&D spillovers'', ''technological spillovers'' ''international R&D'' and ''total factor productivity growth''. The sample was restricted to studies published after 1980, as data and regression techniques were often less sophisticated before 1980. Also, only English language papers were selected. The vast majority of the studies found were published in international journals. This search yielded 38 studies: 17 micro level studies, 7 meso level studies and 15 macro level studies (including 1 study containing both micro and meso elasticities). In total, the studies contain 1214 R&D elasticities. Studies of rates of return on R&D were not used, as these cannot be compared to elasticities without additional assumptions. Appendix A provides a comparison between elasticities and rates of return.

Table 2.1 offers an overview of the studies used in the meta-analyses, presenting the mean values of the own R&D output elasticities and of the spillover elasticities per study. Also, the country or countries in the data samples of the studies are shown. The mean values of the direct output elasticities and the spillover elasticities at each of the three levels of analysis (macro, meso and micro level) are also presented. Various macro studies model spillover effects of foreign R&D capital by including an interaction term of foreign R&D capital and the share of imports in production. Since the coefficients in that case are not elasticities, but elasticities divided by import shares, these estimates are not included in Table 2.1. A detailed description of the three types of studies can be found in Appendix B.

In most studies a Cobb-Douglas production function is used, extended with R&D capital as an extra input. The following basic equation can be formulated, taking value added as the output variable:

$$Y_{i,t} = A_{i,t}\, K_{i,t}{}^{\alpha} L_{i,t}{}^{\beta} RDC_{i,t}{}^{\mu} \qquad (1)$$

where:
Y = volume of value added
A = indicator for the level of technology, to the extent that it is not explained by the R&D capital variable included in the equation
K = volume of physical capital
L = volume of labour input
RDC = volume of R&D capital
i = subscript denoting an individual firm, industry or country
t = subscript denoting an individual year

Coefficient μ is the output elasticity of R&D capital at the firm, industry or country level, which we aim to analyse in this paper. Equation (1) abstracts from spillover elasticities, which are modelled by adding separate variables with elasticities for R&D capital in other firms, industries or countries.

In empirical studies it is common to use linear equations with variables expressed in natural logarithms. Equation (1) can be transformed into logarithms as follows:

$$\ln(Y_{i,t}) = \ln(A_{i.t}) + \alpha \ln(K_{i.t}) + \beta \ln(L_{i.t}) + \mu \ln(RDC_{i.t}) \qquad (2)$$

Next, the equation can be written in first differences in order to explain growth of value added between two years:

$$\Delta \ln(Y_{i,t}) = \Delta \ln(A_{i.t}) + \alpha\, \Delta \ln(K_{i.t}) + \beta\, \Delta \ln(L_{i.t}) + \mu\, \Delta \ln(RDC_{i.t}) \qquad (3)$$

Table 2.1 Overview of the studies used in the meta-analyses

Study	Number of output elasticities		Mean of output elasticities		Country or countries in the data samples
	Own R&D	Spill-overs	Own R&D	Spill-overs	
Micro level					
Bartelsman et al. (1996)	20	-	0.070	-	Netherlands
Bloom et al. (2013)	5	11	0.046	0.307	USA
Branstetter (2001)	2	4	0.187	0.371	Japan and USA (separately)
Capron and Cincera (1998)	29	52	0.249	0.176	Worldwide
Cuneo and Mairesse (1984)	28	-	0.125	-	France
Griliches (1986)	9	-	0.121	-	USA
Griliches and Mairesse (1984)	24	-	0.121	-	USA
Hall (1993)	30	-	0.063	-	USA
Hall and Mairesse (1995)	88	-	0.117	-	France
Harhoff (1998)	27	-	0.098	-	West Germany
Harhoff (2000)	5	4	0.068	–0.016	West Germany
Los and Verspagen (2000)	12	48	0.022	0.389	USA
Mairesse and Hall (1996)	60	-	0.030	-	France and USA (separately)
Ortega-Argilés et al. (2010)	8	-	0.104	-	14 European countries
Rogers (2010)	12	12	0.152	0.004	UK
Schankerman (1981)	12	-	0.103	-	USA
Wang and Tsai (2004)	6	-	0.186	-	Taiwan
All 17 micro level studies	*377*	*131*	*0.103*	*0.250*	
Meso level					
Braconier and Sjöholm (1998)	1	3	–0.061	–0.018	France, Germany, Italy, Japan, UK and USA
Frantzen (2002)	9	25	0.162	0.169	14 OECD countries
López-Pueyo et al. (2008)	18	38	0.114	0.205	Canada, Finland, France, Italy, Spain and USA
Ortega-Argilés et al. (2010)	7	-	0.087	-	9 EU countries
Soete and ter Weel (1999)	6	5	0.069	0.124	Netherlands
Verspagen (1995)	56	-	0.031	-	11 OECD countries
Verspagen (1997)	24	48	0.076	0.073	14 OECD countries
All 7 meso level studies	*121*	*119*	*0.066*	*0.135*	
Macro level					
Ang and Madsen (2013)	23	23	0.163	0.139	China, India, Japan, South Korea, Singapore and Taiwan
del Barrio-Castro et al. (2002)	12	-	0.094	-	20 OECD countries and Israel
Coe and Helpman (1995)	18	6	0.133	0.054	21 OECD countries and Israel
Coe et al. (2009)	33	13	0.103	0.142	Varying across estimations: 21 or 23 OECD countries and Israel
Edmond (2001)	26	8	0.180	0.081	21 OECD countries and Israel
Engelbrecht (1997)	29	2	0.167	0.074	20 OECD countries and Israel
Frantzen (2000)	18	12	0.120	0.182	21 OECD countries
Funk (2001)	24	9	0.135	0.058	21 OECD countries and Israel
Guellec and van Pottelsberghe de la Potterie (2004)	31	15	0.095	0.277	16 OECD countries
Kao et al. (1999)	19	6	0.130	0.082	21 OECD countries and Israel
Keller (1998)	10	4	0.089	0.143	21 OECD countries and Israel
Khan and Luintel (2006)	14	7	0.080	0.024	16 OECD countries
Lichtenberg and van Pottels-berghe de la Potterie (1998)	22	4	0.139	0.069	21 OECD countries and Israel
Mendi (2007)	16	6	0.205	0.369	16 OECD countries
Park (1995)	34	22	0.091	0.195	10 OECD countries
All 15 macro level studies	*329*	*137*	*0.135*	*0.154*	

Estimates in levels and first differences both frequently occur in the studies included in the meta-analyses. In some studies the differences in equation (3) are calculated over longer periods of time (Hall and Mairesse, 1995; Harhoff, 1998; Griliches, 1986).

Output variables vary greatly between and within the various studies. Besides value added and sales, labour productivity and total factor productivity are frequently used. In many studies spillover elasticities are estimated in addition to direct output elasticities. This applies to the majority of the studies at the macro and meso level, as is shown in Table 2.1. In studies at the micro level spillovers are relatively often not analysed.

3. Methodology of the meta-analyses

The dependent variable in the meta-analyses is the output elasticity of R&D. A distinction is made between the output elasticity of own R&D and the output elasticity of outside R&D. The largest part of the analyses is focused on the output elasticity of own R&D. The output elasticity of outside R&D is separately analysed in Section 6. The explanatory variables in both parts of the analyses are characteristics of the original studies and specific characteristics of regressions within the studies. We refer to Appendix B for an extensive description of characteristics of the various studies at the micro, meso and macro level. This section provides a brief overview of the most important explanatory variables used to capture the study design and characteristics of the estimated equations in the analyses of output elasticities of own R&D. The explanatory variables in the analysis of output elasticities of outside R&D are generally comparable. Complete lists of the explanatory variables are shown in the estimation results in Sections 5 and 6.

The first characteristic in the analyses of output elasticities of own R&D concerns the level of analysis: micro, meso or macro. At the macro and meso level we make a distinction between G7 countries and non-G7 countries. The reasoning here is that in countries with large economies R&D spillovers remain for a larger part within national boundaries. As a result, the output elasticity of domestic R&D may be higher in G7 countries than in smaller countries. Next, a distinction is made between private and public R&D. Regarding input measurement a distinction is made between R&D capital and R&D expenditure and between different depreciation rates of R&D capital. Furthermore, it is taken into account whether or not a specific R&D deflator is used and whether or not the production factors labour and capital (and, if applicable, intermediate inputs) are corrected for double counting of R&D. Output measurement variables distinguish between value added, sales or gross production, total factor productivity, labour or capital productivity, total factor productivity and partial productivity. Variables describing production function characteristics include whether or not human capital is an explanatory variable in the regression, whether or not constant returns to scale are imposed, whether or not intermediate inputs are taken into account as separate inputs in case of sales or gross output as output measure (directly or within a productivity measure) and whether or not domestic or foreign spillovers are included in the regression. Estimation characteristics include various aspects, such as whether or not the study uses panel data with fixed effects, a distinction between level and growth estimates and whether or not time dummies or a time trend is included. Subsequently, estimation methods distinguish between econometric techniques such as OLS, dynamic OLS, GMM and Two- or Three-Stage Least Squares. Finally, in studies at the meso and micro level we take into account whether estimates are specifically related to high tech, medium tech or low tech industries.

The explanatory variables in the meta-analyses are dummies with value 1 or 0. To perform a meta-analysis, a baseline needs to be chosen for each of these dummies. The estimated constant term reflects the output elasticity on the baseline. The choice of the baseline is to some extent arbitrary. In this paper the baseline represents characteristics of studies that are often present in studies, particularly studies at the macro level. Macro level studies are a useful starting point for the choice of the variables on the baseline, because the macro level shows the full effect of domestic R&D in a country. With respect to output elasticities of own R&D we perform separate meta-analyses at the micro, meso and macro level together and for these three levels separately. In the analyses for all three levels together and at the macro level total factor productivity is used as output measure on the baseline. This is inspired by a lot of studies at the macro level that use total factor productivity as output measure. At the micro and meso level labour productivity will be the starting point. In studies at these levels total factor productivity is nearly absent as output measure (in studies at the micro level even completely absent).

As a first step, we analyse whether the data suffer from publication bias, using ‘funnel graphs’ (Stanley and Doucouliagos, 2012). The next step is performing meta-regressions. Common methods for meta-analysis are fixed effects models and random effects models. Fixed effects models assume that all studies have identical underlying effect sizes, and that different results across studies are purely due to random errors. Random effects models take account of heterogeneity between studies and assume in that context that studies have different underlying effects that are normally distributed (Pang, Drummond and Song, 1999). As we consider the assumption of identical underlying effect sizes not very realistic, the random effects model is preferred. This will be applied by treating each individual estimate within a study as a separate ‘study’, since heterogeneity of estimates exists not only between studies, but also within studies. For comparison fixed effects estimates are also included.

Fixed effects estimates can be carried out with or without the inverses of the standard errors of the coefficients as weights, whereas random effects estimates use weights calculated as the inverses of a combination of the standard errors of the coefficients and a measure of between-study variation. Weighting by the inverses of the standard errors means that coefficients with higher precision get higher weights in the estimates. The random effects weighting adds a measure of between-study variation to the standard errors of the coefficients, which is an equal value for all coefficients.[1] This mitigates the effect of the standard error of the coefficient in the weighting somewhat (Ringquist, 2013, p. 125). Random effects weighting is most commonly performed using a restricted maximum likelihood (REML) method for the estimation of the between-study variation (Ringquist, 2013, pp. 172-173). This method is applied in the random effect estimates presented in this paper. In the fixed effects estimates that are presented for comparison, the standard errors will not be utilised. As a consequence, Ordinary Least Squares (OLS) instead of Weighted Least Squares (WLS) will be applied in the fixed effect estimates (Ringquist, 2013, pp. 165). An advantage of the OLS estimates is that coefficients for which no standard errors are reported in the underlying studies, can also be included in the meta-analysis. This makes it possible to use more observations than in WLS and random effects meta-regressions. In this paper both OLS and random effects estimates are supplemented by separate estimates in which the inverses of the number of elasticities per study are added as weight, effectively giving each study the same weight.

The *t* statistics presented are based on cluster robust standard errors, in which the correlation between separate estimates within studies (clusters) is taken into account. An exception holds for the meta-analysis of the output elasticity of own R&D at the meso level, where ‘regular’ robust standard errors are used. In that case the number of clusters (studies) is relatively low, which can lead to bias in the calculation of robust standard errors (Ringquist, 2013, p. 199). The inverses of the number of elasticities per study were implemented as weights by including them as ‘probability weights’ in the estimated equations (see, for example, Dupraz, 2013). The empirical estimates were carried out in the software package Stata 12.

4. Test for publication bias

Publication selection is potentially a substantial problem in quantitative research. If unexpected or non-significant results are censored, e.g. by researchers or in reviewing papers for publication, this will bias any summary of empirical results (Stanley and Doucouliagos, 2012). Therefore, it is important to check for possible publication selection. In this section we present ‘funnel graphs’ to detect possible selection.

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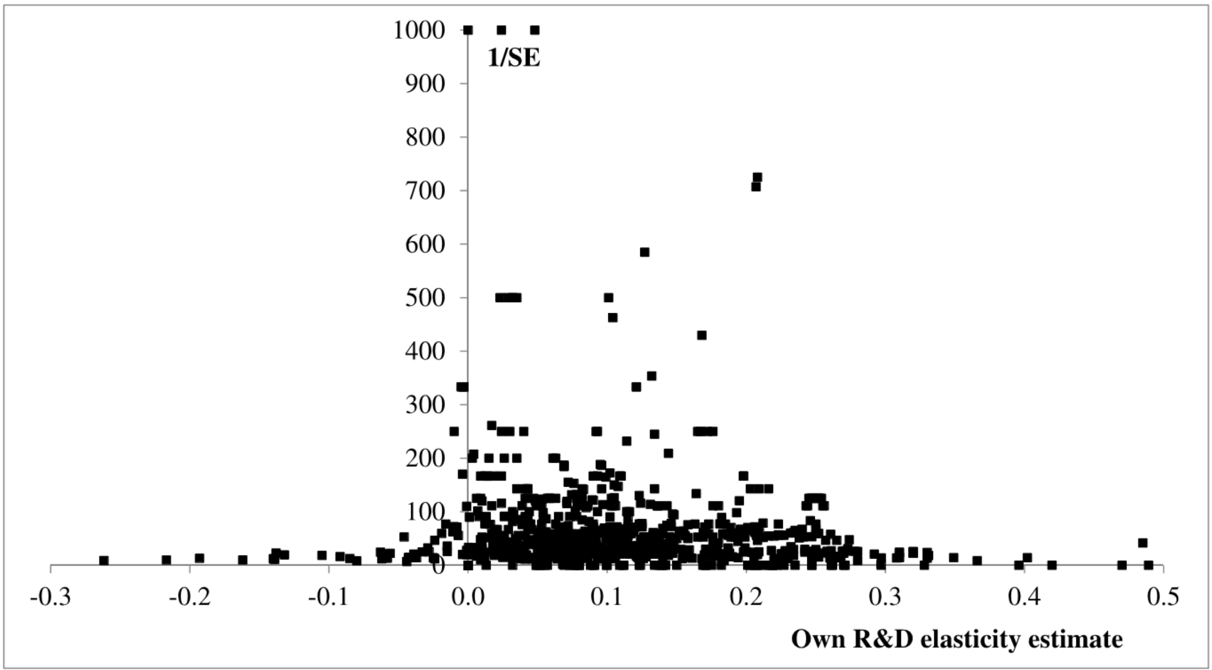
[1] It should be noted that the between-study variation is only included in the weights as far as it is not explained by the meta-regression itself (Ringquist, 2013, pp. 149).

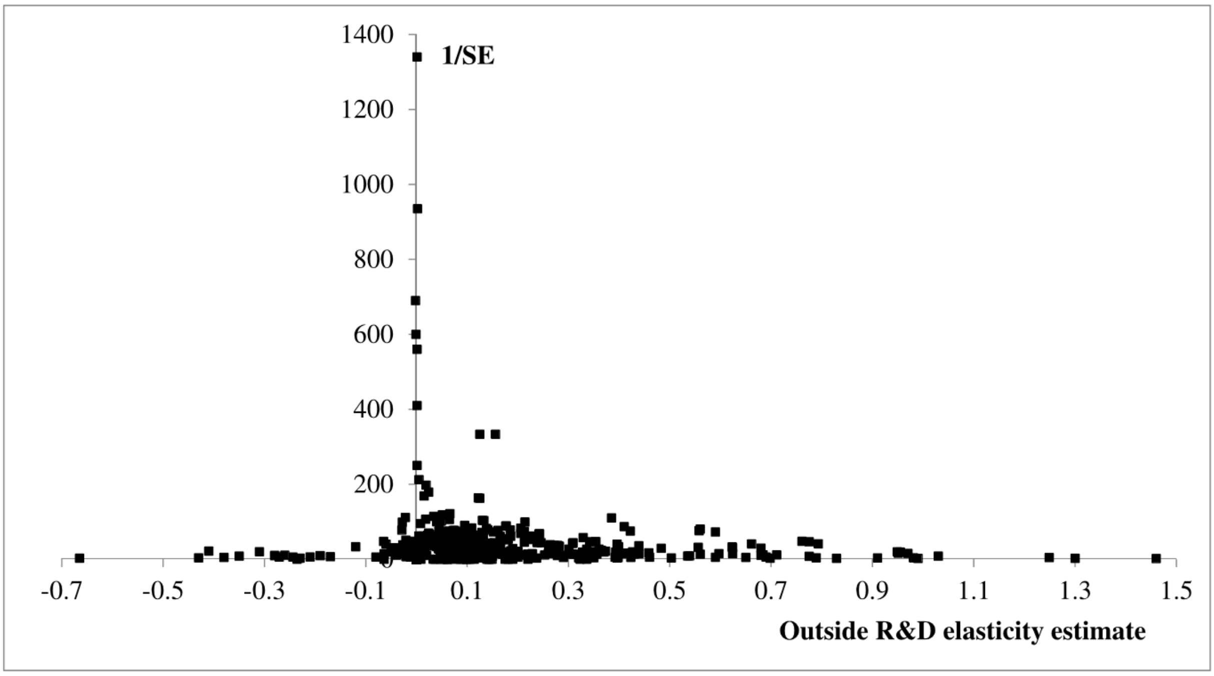
Figures 4.1 and 4.2 show scatter diagrams of elasticity estimates versus the precision of the estimates, measured by the inverse of the standard error (1/SE), for own R&D and outside R&D elasticities, respectively. Some estimates, depicted in the tops of both graphs, show very low standard errors. These have been checked for coding errors or other problems. In two cases own R&D elasticity estimates were discarded because the authors of the studies express strong doubts about these results. Figures 4.1 and 4.2 show the data after these corrections. As the remaining estimates with low standard errors are reported in the studies without critical remarks by the authors, these were not discarded.

Figure 4.1 Funnel graph of own R&D elasticity estimates



Note: SE denotes the standard error of the output elasticity estimate.

Figure 4.2 Funnel graph of outside R&D elasticity estimates



Note: SE denotes the standard error of the output elasticity estimate.

The graph with respect to the elasticities of own R&D looks fairly symmetric, without clear truncation of negative values of the elasticities and without a sign that relatively high elasticities are overrepresented. The graph with respect to the elasticities of outside R&D is less symmetric. On the right-hand side of the graph higher standard errors (i.e. lower values of 1/SE) seem to be correlated to some extent with higher values of output elasticities. The reason for such a positive correlation between the standard error and the value of the output elasticity may be that a higher standard error requires a higher output elasticity for a significant result and that non-significant results are having a lower probability of being published.

The possible occurrence of publication bias can formally be tested by conducting regressions in which the relationship between the values of the standard errors and the values of the estimated output elasticities is investigated empirically (Stanley and Doucouliagos, 2012). In Table 4.1 empirical results are presented for the observations depicted in Figures 4.1 and 4.2. In the estimates with respect to the output elasticities of own R&D insignificant results for the standard error as explanatory variable indicate that publication bias is not present. In the estimates with respect to the output elasticities of outside R&D a significant positive relationship between the standard error of the output elasticity and the estimated output elasticity appears, which could be a sign of publication bias.

Table 4.1 Estimation results of relationship between output elasticities of R&D and the standard errors of these elasticities as test for publication bias

	Output elasticity of own R&D as dependent variable				**Output elasticity of outside R&D as dependent variable**			
	Equal weights for each observation		**Equal weights for each study**		**Equal weights for each observation**		**Equal weights for each study**	
	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic
Explanatory factors								
Constant	0.107	11.77	0.105	11.56	0.138	3.39	0.120	2.34
Standard error	–0.100	–0.44	0.076	0.37	0.758	4.12	0.719	2.02
Number of observations	764		764		358		358	
R^2	0.001		0.001		0.081		0.092	

Note: the *t* statistics are based on cluster robust standard errors.

In the meta-regressions in Sections 5 and 6 the possibility of publication bias will be given further attention by including the standard error of the output elasticity as an additional explanatory variable, alongside all the other explanatory variables for the output elasticities (study characteristics). This is done in supplementary estimates. In the meta-analyses of the output elasticities of own R&D no publication bias is found. On the other hand, an indication of publication bias reappears in the meta-analysis for the output elasticity of outside R&D. However, including the standard error as additional explanatory variable in that analysis does not change the general picture of the results for the other explanatory factors substantially.

5. Estimation results of meta-analyses for output elasticities of own R&D

The empirical analysis starts with regressions for the output elasticity of own R&D at all three data levels together. Table 5.1 contains the results of this analysis. Thereafter, an analysis at the macro level is conducted, the results of which are presented in Table 5.2. Regressions at the meso and micro will be briefly discussed. The results of these regressions are presented in Appendix C. From an economic policy point of view, the estimates at the three levels together and the macro level are the most relevant. From these estimates conclusions can be drawn for the output elasticity of domestic R&D at the macro level, which (implicitly) includes domestic intersectoral and intrasectoral spillovers. For this reason, attention is focused strongly here on the regressions at the three levels together and the macro level.

Table 5.1 Estimation results of meta-analysis for output elasticities of own R&D; all data levels

	OLS, basic		**OLS, with equal weights for each study**		**Random effects, basic**		**Random effects, with equal weights for each study**	
	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic
Constant	0.088	3.72	0.089	3.76	0.093	3.05	0.085	3.12
Data level (reference: macro)								
Micro	0.018	0.53	0.005	0.16	0.055	1.71	0.034	1.15
Meso	0.037	1.07	0.013	0.45	0.049	1.58	0.039	1.58
Effect of G7/non-G7 at macro or meso level (reference: G7 and non-G7 countries combined)								
G7 countries or country, macro level	0.112	7.58	0.111	7.07	0.109	6.90	0.117	8.40
Non-G7 countries or country, macro level	–0.016	–1.91	–0.016	–1.66	–0.019	–1.78	–0.015	–1.57
G7 countries or country, meso level	–0.024	–0.74	–0.100	–2.98	–0.014	–0.45	–0.105	–2.86
Non-G7 countries or country, meso level	–0.020	–0.73	–0.053	–2.24	–0.013	–0.54	–0.048	–2.16
Private or public R&D (reference: private R&D)								
Public R&D	0.010	0.34	0.014	0.43	0.045	1.81	0.030	1.26
Total R&D (i.e. private and public R&D)	–0.032	–0.88	–0.033	–0.95	–0.067	–2.67	–0.079	–3.20
Input measurement (reference: R&D capital, 10 to 20% depreciation rate of R&D capital, no specific R&D deflator, no correction for double counting of R&D)								
R&D expenditure	–0.031	–1.82	0.018	0.63	–0.019	–1.32	0.012	0.67
Deprecation rate of R&D capital:								
- less than 10%	–0.027	–1.71	–0.029	–1.89	–0.021	–1.09	–0.023	–1.38
- 20% or more	–0.003	–0.20	–0.004	–0.24	0.002	0.16	0.009	0.62
Specific R&D deflator	0.031	2.38	0.027	2.05	0.025	2.01	0.026	2.02
Correction for double counting of R&D	0.031	2.56	0.031	2.77	0.034	3.27	0.032	3.49
Output measurement (reference: total factor productivity)								
Value added	–0.014	–0.44	0.031	1.14	–0.033	–1.06	0.028	1.14
Sales or gross production	–0.057	–1.77	–0.001	–0.03	–0.067	–2.30	–0.018	–0.59
Labour productivity or capital productivity	–0.003	–0.10	0.040	1.58	–0.015	–0.56	0.028	1.20
Partial productivity	–0.030	–1.02	0.004	0.12	–0.037	–1.35	0.018	0.50

Table continues on next page.

Table 5.1 (continued) Estimation results of meta-analysis for output elasticities of own R&D; all data levels

	OLS, basic		**OLS, with equal weights for each study**		**Random effects, basic**		**Random effects, with equal weights for each study**	
	Coefficient	*t* statistic	Coefficient	*t* statistic	Coefficient	*t* statistic	Coefficient	*t* statistic
Production function characteristics (reference: human capital not implemented in regression, in case of sales or gross output as output measure (directly or within a productivity measure) intermediate inputs not taken into account, constant returns to scale in factor inputs imposed, private and public R&D not taken into account together, international R&D spillovers taken into account, at meso level domestic intersectoral R&D spillovers taken into account, at micro level domestic intrasectoral and intersectoral R&D spillovers not taken into account)								
Human capital in regression	–0.024	–1.76	–0.033	–1.97	–0.015	–1.20	–0.018	–1.21
In case of sales or gross output as output measure (directly or within a productivity measure): intermediate inputs taken into account	–0.044	–2.33	–0.149	–1.65	–0.043	–3.24	–0.086	–1.73
Constant returns to scale not imposed	–0.048	–9.79	–0.048	–3.61	–0.046	–7.01	–0.045	–4.05
In case of private R&D: also public R&D taken into account	–0.006	–0.11	0.001	0.01	–0.053	–1.11	–0.030	–0.59
In case of public R&D: also private R&D taken into account	–0.073	–1.61	–0.093	–1.96	–0.100	–2.59	–0.115	–2.01
International R&D spillovers not taken into account	–0.024	–0.59	–0.032	–0.79	–0.066	–1.90	–0.058	–1.78
At meso level domestic intersectoral R&D spillovers not taken into account	–0.004	–0.11	–0.009	–0.32	–0.003	–0.10	–0.009	–0.39
At micro level domestic intrasectoral and/or intersectoral R&D spillovers taken into account	0.109	2.89	0.039	1.37	0.076	2.95	0.028	1.40
Estimation characteristics (reference: panel, fixed effects, homogeneity of output elasticity, estimation in levels, lagged R&D input, no time dummies or time trend included in regression)								
Cross-sectional or totals estimates	0.044	1.86	0.017	1.10	0.049	2.04	0.016	1.14
Random effects (level or growth estimate)	0.016	0.64	–0.026	–0.91	0.018	0.55	–0.032	–1.16
Mean Group Estimate / heterogeneous panel estimate (level estimate)*	0.151	6.78	0.148	5.87	0.096	10.66	0.105	8.33
Growth estimate	0.032	1.56	0.005	0.25	0.025	1.15	–0.006	–0.33
In case of growth estimate: long differences	0.005	0.31	0.014	0.51	0.012	0.71	0.007	0.32
Unlagged R&D input in case of level estimate	–0.003	–0.23	0.011	0.63	–0.000	–0.03	0.004	0.20
Unlagged R&D input in case of growth estimate	0.098	2.53	0.135	2.34	0.106	3.01	0.131	2.44
Time dummies or time trend included in level estimate	0.044	1.90	0.026	1.33	0.054	3.44	0.043	3.32
Time dummies or time trend included in growth estimate	0.001	0.02	–0.006	–0.16	0.014	0.50	0.027	0.86

Table continues on next page.

Table 5.1 (continued) Estimation results of meta-analysis for output elasticities of own R&D; all data levels

	OLS, basic		**OLS, with equal weights for each study**		**Random effects, basic**		**Random effects, with equal weights for each study**	
	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic
Estimation method (reference: Ordinary Least Squares (OLS))								
Dynamic OLS (DOLS)	0.022	1.60	0.033	2.33	0.017	1.23	0.020	1.36
Fully Modified OLS (FMOLS) or Engle-Granger-Yoo three step procedure	–0.016	–1.40	–0.013	–1.04	–0.009	–1.01	–0.005	–0.60
Difference Generalized Method of Moments (GMM-DIF) or System Generalized Method of Moments (GMM-SYS)**	–0.126	–4.45	–0.064	–1.17	–0.135	–5.30	–0.108	–2.51
Two-Stage or Three-Stage Least Squares (2SLS or 3SLS)	–0.020	–1.19	0.003	0.22	–0.003	–0.19	0.010	0.86
Other (residual category): Generalized Least Squares (GLS), Feasible Generalized Least Squares (FGLS), Weighted Lest Squares (WLS) or Seemingly Unrelated Regression (SUR)	–0.000	–0.00	0.028	1.11	–0.001	–0.04	0.028	1.23
Sectors (reference: no distinction)								
High tech	0.033	2.40	0.062	3.47	0.029	2.73	0.046	4.00
Medium tech	–0.016	–0.94	0.005	0.34	–0.013	–0.88	0.003	0.20
Low tech	–0.049	–4.17	–0.036	–3.11	–0.049	–5.01	–0.037	–3.30
Medium and low tech combined	–0.060	–3.51	–0.065	–2.21	–0.067	–4.20	–0.069	–2.83
Number of observations	827		827		764		764	
R^2	0.525		0.551		0.829		0.831	
Additional estimate with the standard error of the output elasticity included as explanatory variable, in the context of possible publication bias (only estimation results for the standard error and the constant are shown, together with the R^2 and the number of observations):								
Standard error of coefficient	–0.146	–1.03	–0.026	–0.37	0.083	0.25	0.174	0.45
Constant	0.088	2.96	0.094	3.06	0.093	3.08	0.084	3.10
Number of observations	764***		764***		764		764	
R^2	0.536		0.580		0.829		0.844	

* In case of random effects estimates no heterogeneous panel estimate available in observations at all three data levels.
** In case of random effects estimates no System Generalized Method of Moments (GMM-SYS) estimates available in observations at all three data levels.
*** Limited by availability of standard errors for coefficients. Therefore, the number of observations is the same here as in the case of random effects estimates.

Notes (general):
- The *t* statistics are based on cluster robust standard errors.
- The standard errors of the observations used in the random effects estimates are constrained to a minimum value of 0.002. This has hardly any effect on the results.

Table 5.2 Estimation results of meta-analysis for output elasticities of own R&D; macro studies only

	OLS, basic		OLS, with equal weights for each study		Random effects, basic		Random effects, with equal weights for each study	
	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic
Constant	0.138	7.91	0.136	7.40	0.112	7.02	0.114	6.20
Effect of G7/non-G7 at macro level (reference: G7 and non-G7 countries combined)								
G7 countries or country, macro level	0.102	7.31	0.103	7.18	0.111	8.21	0.118	10.27
Non-G7 countries or country, macro level	–0.029	–3.09	–0.026	–2.51	–0.016	–2.31	–0.014	–1.74
Private or public R&D (reference: private R&D)								
Public R&D	–0.055	–1.77	–0.058	–1.97	–0.032	–6.35	–0.034	–7.59
Total R&D (i.e. private and public R&D)	–0.100	–2.58	–0.110	–2.96	–0.068	–8.91	–0.067	–8.60
Input measurement (reference: R&D capital, 10 to 20% depreciation rate of R&D capital, no specific R&D deflator, no correction for double counting of R&D)								
R&D expenditure	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Depreciation rate of R&D capital:								
- less than 10%	–0.047	–5.10	–0.048	–5.20	–0.034	–4.80	–0.033	–5.04
- 20% or more	0.030	1.11	0.032	1.27	Collinearity; variable coincides with ‘Total R&D’*			
Specific R&D deflator	0.005	0.50	0.002	0.19	0.008	0.88	0.000	0.03
Correction for double counting of R&D	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Output measurement (reference: total factor productivity)								
Value added	Collinearity; variable coincides with ‘Constant returns to scale not imposed’**				n.a.	n.a.	n.a.	n.a.
Sales or gross production	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Labour productivity***	0.029	0.72	0.027	0.68	0.086	6.38	0.084	4.91
Partial productivity	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

Table continues on next page.

Table 5.2 (continued) Estimation results of meta-analysis for output elasticities of own R&D; macro studies only

	OLS, basic		**OLS, with equal weights for each study**		**Random effects, basic**		**Random effects, with equal weights for each study**	
	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic
Production function characteristics (reference: human capital not implemented in regression, in case of sales or gross output as output measure (directly or within a productivity measure) intermediate inputs not taken into account, constant returns to scale in factor inputs imposed, private and public R&D not taken into account together, international R&D spillovers taken into account)								
Human capital in regression	–0.038	–2.34	–0.040	–2.47	–0.023	–2.66	–0.031	–2.63
In case of sales or gross output as output measure (directly or within a productivity measure): intermediate inputs taken into account	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Constant returns to scale not imposed	–0.016	–2.36	–0.010	–1.13	n.a.	n.a.	n.a.	n.a.
In case of private R&D: also public R&D taken into account	–0.027	–1.32	–0.015	–0.58	–0.022	–1.93	–0.004	–0.14
In case of public R&D: also private R&D taken into account	–0.030	–0.44	–0.037	–0.58	0.022	0.54	0.005	0.10
International R&D spillovers not taken into account	0.081	2.01	0.087	2.24	0.040	4.29	0.045	5.79
Estimation characteristics (reference: panel, fixed effects, homogeneity of output elasticity, estimation in levels, lagged R&D input, no time dummies or time trend included in regression)								
Cross-sectional or totals estimates	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Random effects (level or growth estimate)	0.007	0.26	0.004	0.17	–0.001	–0.09	–0.002	–0.19
Mean Group Estimate / heterogeneous panel estimate (level estimate)****	0.132	13.85	0.138	13.73	0.103	23.23	0.109	15.34
Growth estimate	0.036	1.25	0.037	1.44	0.023	1.83	0.029	1.79
In case of growth estimate: long differences	0.014	0.64	0.019	1.07	0.011	1.36	0.011	1.28
Unlagged R&D input in case of level estimate	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Unlagged R&D input in case of growth estimate	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Time dummies or time trend included in level estimate	–0.010	–0.38	–0.017	–0.72	–0.010	–0.58	–0.017	–0.85
Time dummies or time trend included in growth estimate	–0.117	–2.31	–0.116	–2.26	–0.128	–4.56	–0.136	–4.13

Table continues on next page.

Table 5.2 (continued) Estimation results of meta-analysis for output elasticities of own R&D; macro studies only

	OLS, basic		**OLS, with equal weights for each study**		**Random effects, basic**		**Random effects, with equal weights for each study**	
	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic
Estimation method (reference: Ordinary Least Squares (OLS))*****								
Dynamic OLS (DOLS)	0.007	0.75	0.011	1.12	0.011	1.12	0.010	0.76
Fully Modified OLS (FMOLS)	0.001	0.10	0.007	0.72	0.003	0.38	0.006	0.56
System Generalized Method of Moments (GMM-SYS)	–0.018	–0.51	–0.014	–0.51	n.a.	n.a.	n.a.	n.a.
Two-Stage or Three-Stage Least Squares (2SLS or 3SLS)	0.033	2.09	0.023	1.08	0.048	6.64	0.041	2.86
Other (residual category): Generalized Least Squares (GLS), Feasible Generalized Least Squares (FGLS) or Seemingly Unrelated Regression (SUR)	0.041	1.98	0.046	2.79	0.038	4.76	0.041	6.06
Number of observations	329		329		268		268	
R^2	0.622		0.629		0.927		0.925	
Additional estimate with the standard error of the output elasticity included as explanatory variable, in the context of possible publication bias (only estimation results for the standard error and the constant are shown, together with the R^2 and the number of observations):								
Standard error of coefficient	–0.650	–0.71	–1.268	–1.65	0.359	0.60	–0.124	–0.18
Constant	0.140	6.54	0.138	6.84	0.111	7.38	0.113	6.53
Number of observations	268******		268******		268		268	
R^2	0.639		0.695		0.927		0.926	

* Perfect collinearity, caused by coincidence of characteristics in the study by Ang and Madsen (2013).

** Perfect collinearity, caused by coincidence of characteristics in the study by Coe and Helpman (1995).

*** No capital productivity available in observations at the macro level.

**** No heterogeneous panel estimate available in observations for the random effects estimates at the macro level as well as the two other levels.

***** No Engle-Granger-Yoo three step procedure, Difference Generalized Method of Moments (GMM-DIF) and Weighted Least Squares (WLS) estimates available in observations at the macro level.

****** Limited by availability of standard errors for coefficients. Therefore, the number of observations is the same here as in the case of random effects estimates.

Notes (general):
- The *t* statistics are based on cluster robust standard errors.
- The standard errors of the observations used in the random effects estimates are constrained to a minimum value of 0.002. This has hardly any effect on the results.

The analysis at the three levels together has the advantage that the number of observations is large. A disadvantage of his approach is, however, that output elasticities of own R&D at the three separate levels are treated as similar, whereas they are very different from each other with respect to the extent to which spillovers are included and the coverage of firms or industries in the estimates. Output elasticities of own R&D at the micro level do not contain spillovers. They cover firms at the micro level performing R&D, with an emphasis on manufacturing firms. Output elasticities of own R&D at the meso level include intrasectoral spillovers. In empirical studies at this level manufacturing industries are overrepresented. Output elasticities at the macro level include intrasectoral and intersectoral spillovers. These studies represent the total business sector or the total economy. In principle, a meta-analysis based on studies at the macro level can be preferred for insight into the determinants of results in the literature for the output elasticity of domestic R&D at the macro level , but the disadvantage of a smaller number of observations is an issue that should be taken in consideration.

As shown in Figure 4.1, some output elasticities have a very high degree of accuracy: a standard error of 1/500 (0.002) or less. This is still the case after discarding a few elasticities of own R&D because of doubt expressed by the authors of the studies. It is questionable whether the remaining very low standard errors are correct in all cases. In order to prevent that the estimates with very low standard errors weigh excessively heavy in the random effects estimates, standard errors with values lower than 0.002 are constrained to a minimum value of 0.002. Sensitivity analyses show that this has hardly any effect on the results of the meta-analyses.

In the bottom sections of the tables estimation results are presented for the standard error of the output elasticity as additional explanatory variable, combined with the results for the constant term and the R^2 of the estimated equation. An indication for publication bias would be present in case of a significant positive coefficient of the standard error of the output elasticity. In none of the estimates such a result is obtained.

All data levels

The results of the meta-analysis for the output elasticity of own R&D on all three data levels together are reported in Table 5.1. The constant term is approximately 0.09. The level of analysis (macro, meso or micro) does not have a significant effect on the output elasticity. With regard to the macro level this refers to estimates for G7 and non-G7 countries combined. At the macro level there is a strongly significant positive effect of 0.11-0.12 on the output elasticity of estimates referring to G7 countries. This confirms that G7 countries, being large, benefit more from domestic R&D spillovers than smaller countries. It is plausible that a differentiation is relevant between the very large G7 countries (the United States and to a lesser extent Japan) and the other G7 countries (Canada, Germany, France, Italy and the United Kingdom). A relatively very high output elasticity of domestic R&D could be applicable in the United States as by far the largest OECD country, whereas the output elasticity in the other G7 countries can be supposed to be more moderately higher than those in non-G7 countries. Because of data limitations we abstract from this differentiation within G7 countries in the meta-analyses. It is remarkable that a positive G7 effect is not found at the meso level, which result will be confirmed in the separate analysis at the meso level. A distinction between G7 and non-G7 countries has not been made in the 'own R&D' estimates at the micro level, since these estimates do not contain spillovers.

Subsequently, the table shows a non-significant positive coefficient for public R&D and a negative significant effect of total R&D (both relative to private R&D). In case of public R&D the result should be observed in combination with a significant negative effect of taking into account private R&D besides public R&D (presented further on in the table). On balance a substantial negative effect results for public R&D (compared to private R&D) if both private R&D and public R&D are included in the estimated equation.

The results under 'Input measurement' indicate that a correction for double counting of R&D, which mainly occurs in a part of the estimates at micro level in the underlying studies (see Appendix B), has a significant positive effect on the output elasticity. This corresponds to what could be expected on theoretical grounds. The same holds for the significant positive effect that is found for using a specific deflator for R&D (instead of the general price level in a country or sector). It is common that specific R&D deflators increase faster than general price levels, which usually leads to a slower development of the volume of R&D expenditure when a specific R&D deflator is used. The results furthermore suggest that it does not matter much whether R&D expenditures or R&D capital has been chosen as input measure of R&D and which depreciation rate has been used for R&D capital. It also seems of relatively little influence which measure of output has been chosen as dependent variable: total factor productivity (on the baseline) or value added, gross output / sales, labour productivity or capital productivity. Most results shown in this category 'Output measurement' are not significant.

Among the production function characteristics, a significant negative effect appears for not imposing constant returns to scale in the factor inputs labour and capital and, if applicable, intermediate inputs. A significant negative effect is also found for another production function characteristic that is often relevant in micro level estimates: taking account of intermediate inputs as a separate production factor in estimates with sales or gross output as output measure. As described in Appendix B (Section B.1), in the latter case output elasticities are not comparable with those for value added. The significant negative effect found for treating intermediate inputs as a separate production factor in this context is in line with theoretical reasoning. Another negative effect that could be expected is that of including human capital in the regression. However, the coefficient for this effect is not significant. As already noted, including private R&D besides public R&D reduces the output elasticity found for public R&D significantly. In a similar way, including public R&D besides private R&D can be expected to reduce the output elasticity found for private R&D, but in the meta-analysis this effect is not significant. Difficult to interpret are the results with respect to taking account of spillovers of R&D. Theoretical reasoning would predict that not taking account of international and/or domestic spillovers increases the output elasticity found for own R&D (in econometric terms because of 'omitted variables bias'), but counter-intuitive results in the opposite direction are provided by the meta-analysis. These results are partly significant.

Results concerning estimation characteristics are varying and often not significant. A clear significant positive effect appears for estimates that take account of heterogeneity between countries. These are Mean Group Estimates and heterogeneous panel estimates, which appear only at the macro level in the studies included in the meta-analysis. Furthermore, significant positive effects are found for using unlagged R&D input in growth estimates and including time dummies or a time trend in level estimates. The latter result is opposite to what could be expected analytically, assuming that time dummies and time trend variables capture positive contributions to the development of output not explained by other explanatory variables. Therefore, this result is difficult to interpret. The significant positive effect of using unlagged R&D input in growth estimates can be conceived in combination with a significant negative effect of GMM estimates in the category 'Estimation method'. In fact, both results are strongly determined by GMM-DIF estimates with unlagged R&D capital variables in the micro studies by Mairesse and Hall (1996) and Capron en Cincera (1998). However, also relative high output elasticities in growth estimates conducted with OLS and WLS estimates in the studies by Capron en Cincera (1998) and Bartelsman et al. (1996) contribute to a significant positive effect of the variable 'Using unlagged R&D input in growth estimates' in the meta-analysis. Apart from GMM, the estimation method does not have much effect on the output elasticities, according to the results of the meta-analysis. Comparisons of results with different estimation methods within individual studies support this broadly. For example, in the study by Frantzen (2002) output elasticities estimated with OLS and DOLS were found to be remarkably close. According to this author, this suggests that endogeneity bias in the OLS estimates is only modest. As sources of endogeneity he mentions short-run feedback effects from total factor productivity (as output measure) to R&D spending and, in addition to this, common demand shocks affecting these two variables.

Finally, a distinction between high tech, low tech and medium tech sectors is relevant in the meta-analysis. As expected, output elasticities for firms in high tech sectors are higher than for firms distributed across different kinds of sectors while the elasticities for firms in low tech sectors are smaller.

Macro level studies

Table 5.2 contains meta-analysis results for the output elasticity of own R&D at the macro level. Several variables included in the analyses at the three levels together are not part of the characteristics in the selection of studies at the macro level. This is shown in the table with ‘not available’ (abbreviated as ‘n.a.’). Sometimes there is perfect collinearity between variables. Then a characteristic in a study coincides completely with another characteristic in the same study, in which case it is not possible to distinguish the effects of these characteristics from each other.

In the estimates at the macro level the constant term has a higher value than in the estimates at the three levels together. In the OLS estimates the constant term amounts to approximately 0.14 and in the random effects estimates the value is approximately 0.11. To these values an effect of estimates for G7 countries can be added, which is approximately 0.10 in the OLS estimates and 0.11-0.12 in the random effects estimates. For non-G7 countries a negative effect of approximately 0.03 appears in the OLS estimates and a negative effect of around 0.015 in the random effects estimates. The result for public R&D (compared to private R&D as reference) is significantly negative in these estimate at the macro level. Among the production function characteristics there is no longer a significant negative effect of taking account of private R&D besides public R&D.

Results under ‘Input measurement’ deviate substantially from those obtained at the three levels together. Using a depreciation rate of R&D-capital less than 10% instead of 10 to 20 % (baseline) has a significant negative effect of approximately 0.05 in the OLS estimates and approximately 0.03 in the random effects estimates. Furthermore, using a specific R&D deflator no longer has a significant (positive) effect. With respect to output measurement almost all studies use total factor productivity as dependent variable. The study by Park (1995) is the only exception. The significant positive effect of labour productivity that appears in the meta-regression results is based only on this single study, which means that no strong conclusion can be drawn from this result.

The results for production function characteristics show a significant negative effect of including human capital in the regression. This differs from the non-significant negative results for this item in the estimates at the three levels together, with lower absolute values of the coefficients. The negative effect of including human capital amounts to approximately 0.04 in the OLS estimates and 0.02-0.03 in the random effects estimates. This indicates that output elasticities of R&D reflect partly an impact of human capital on productivity if human capital is disregarded among the explanatory variables. A further distinction with the results at the three levels together is that a significant positive effect is found for not taking into account international R&D spillovers. This effect has a magnitude of 0.08-0.09 in the OLS estimates and of 0.040-0.045 in the random effects estimates. Analogous to the interpretation of the result obtained for human capital, this indicates that the output elasticity of own R&D represents partly an impact of international R&D spillovers if international R&D spillovers are disregarded as explanatory factor.

Among the estimation characteristics a strong positive effect is found for using Mean Group Estimates or heterogeneous panel estimates. The values of the coefficients for this variable are similar to those obtained at the three levels together, which can be explained by the fact that all observations for this effect are derived from macro studies. Observations with unlagged R&D input in case of level or in case of growth estimates are not available within the studies at the macro level. This also applies to GMM-DIF as estimation method. The significant positive effect of unlagged R&D input in case of level estimates together with a significant negative effect of GMM-DIF as estimation method in the meta-analysis at the three levels together can therefore not be compared with results in this respect at the macro level. In contrast to the results at the three levels together, a plausible significant negative effect appears now for including time dummies or a time trend in growth estimates, whereas an insignificant negative result is found now for including time dummies or a time trend in level estimates.

At first glance, the significant positive results found for the estimation methods 2SLS/3SLS and, as a residual category, GLS/FGLS/SUR are difficult to interpret. In the meta-analysis at the three levels together only insignificant results (with alternating signs) were obtained for these estimation methods. The methods are used in the following macro studies: Engelbrecht (1997), Guellec and van Pottelsberghe de la Potterie (2004), Khan and Luintel (2006) and Park (1995). Within these studies the results can be compared with OLS estimates as benchmark. Such a comparison shows that the results with 2SLS/3SLS and GLS/FGLS/SUR are similar to those obtained with OLS. The significant positive results found for 2SLS/3SLS and GLS/FGLS/SUR in the analysis at the macro level may reflect specific characteristics of the studies itself, instead of effects of estimation methods.

Micro and meso level studies

Results of a meta-analysis at the micro level, presented in Table C.1 of Appendix C, are largely in line with those in the meta-analysis at the three levels together. This can partly be explained by the fact that almost half of the observations at the three levels together are micro level estimates and that observations for some variables are only available in micro level studies. The latter concerns the following variables: R&D expenditure instead of R&D capital for R&D input, sales or gross production as output measure and, connected to this, taking into account (or not) intermediate inputs in case of sales or gross production as output measure, partial productivity as output measure and using unlagged R&D input in case of a growth estimate.

The analysis at the meso level, presented in Table C.2 of Appendix C, has a relatively small number of observations (121), compared to the analyses at the micro and macro level. This can explain that only for a small number of variables significant results are obtained in this analysis. A limitation in the analysis at the meso level is furthermore that for relatively many variables no observations are available and that in several cases effects of variables cannot be distinguished from each other because of perfect collinearity as a result of coincidences of variables within studies.

Negative results are obtained at the meso level for output elasticities referring to G7 countries. This was already reflected in the meso level results for this effect in the analysis at the three levels together. Observations for G7 countries at the meso level are almost all from the study by Verspagen (1995). In that study no systematic difference can be observed for estimated output elasticities of (own industry) R&D in G7 and non G7 countries. Results from some specific estimates with a G7 dummy at the meso level in the study by Frantzen (2002) suggest that the output elasticity of total domestic R&D (i.e. domestic R&D in the own sector combined with domestic R&D in other sectors) is higher in G7 countries, but that this can be attributed to intersectoral spillovers instead of intrasectoral spillovers. This would imply that a G7 effect is not important for the output elasticity of own R&D at the meso level.

Within the category ‘Input measurement’ in only one estimate at the micro level a significant (positive) effect is found for the use of a specific R&D deflator. This is to a large extent similar to the results in the analysis at the macro level, where only insignificant estimates were found for this variable. From this it can be deduced that the significant positive effect of using a specific R&D deflator obtained in the analysis at the three levels together is concentrated in meso level observations. This is confirmed by largely significant (at 5% level) positive results for this variable in the analysis at the meso level.

Noteworthy is also that among the estimation characteristics cross-sectional or ‘totals’ estimates (i.e. estimates without inclusion of fixed or random effects) have a significant positive effect in all estimates in the analysis at the micro level, whereas in the analysis at the three levels together this effect was only significant positive (at 5% level) in one of the estimates. A significant positive effect is plausible. In the analysis at the meso level counter-intuitive negative results are obtained for this variable, which can explain the rather weak results for this variable in the analysis at the three levels together.

Furthermore, it is remarkable that in the estimates at the micro level significant positive effects are found for using random effects instead of fixed effects within the estimation characteristics. In the analyses at the macro level, the meso level and the three levels together only insignificant results are obtained for this estimation characteristic. The results for this variable at the micro level should be interpreted in combination with negative results for FGLS/WLS/SUR as residual group of estimation methods. Estimation with random effects implies the use of FGLS as estimation method. This applies to ten estimates in the studies at the micro level: half of the estimates in the study by Ortega-Argilés et al. (2010) and all estimates in the study by Wang and Tsai (2004). To a certain extent similar to this, a significant positive effect of using unlagged R&D input in case of a growth estimate is found in combination with a significant negative effect of GMM-DIF as estimation method. In the context of the results at the three levels together this has already been discussed as a confluence of variables in studies at the micro level. It shows up again now in the results of the analysis at the micro level.

6. Estimation results of meta-analysis for output elasticities of outside R&D

Table 6.1 and Appendix D show the results of a meta-analysis for output elasticities of outside R&D. This part of the analyses has been carried out only at the three data levels (micro, meso and macro) together, because the numbers of observations are relatively small at the three levels separately. Table 6.1 presents results without a control for possible publication bias. Supplementary information in the bottom section of the table shows significant positive results for the standard error of the coefficient (i.e. the standard error of the estimated output elasticity of outside R&D) as an additional explanatory variable. This is an indication that publication bias can be relevant here. Therefore, in Table D.1 of Appendix D full results are presented with the standard error of the coefficient included as explanatory variable. The results with this control for publication bias are broadly similar to those presented in Table 6.1.

For a large part the explanatory variables are identical or similar to those in the meta-analyses for output elasticities of own R&D. Mainly in the upper sections of the tables explanatory variables are modified or added specifically for the explanation of output elasticities of outside R&D. This concerns the sections with the following headings: ‘Type of R&D spillovers’, ‘Effect of G7’ and ‘Transmission channel for spillovers’.

Under the heading of ‘Type of spillovers’ the three data levels are reflected. A distinction is made between domestic and international spillovers on the one hand and between intrasectoral and intersectoral spillovers (including a combination of intrasectoral and intersectoral spillovers) on the other. The latter distinction applies to spillovers at the micro or meso level, from individual firms or industries. These spillovers can occur domestically and internationally. At the macro level output elasticities of outside R&D refer to international spillovers (implicitly comprising international intrasectoral and intersectoral spillovers). International spillovers at the macro level are chosen as reference on the baseline, which is consistent with the choice of the macro data level on the reference path in the meta-analysis for output elasticities of own R&D at all three data levels together.

From the results it appears that output elasticities of domestic outside R&D from individual firms are generally lower than those of domestic outside R&D from industries. This may be caused by difficulties in the measurement of relevant outside R&D from individual firms compared to the measurement of outside R&D from industries. It is particularly difficult to construct appropriate weights for the calculation of outside R&D with data available at the micro level. It also appears that the output elasticities of domestic outside R&D from industries in case of a combination of intrasectoral and intersectoral spillovers to individual firms are significantly higher than the output elasticities of foreign R&D at the macro level on the baseline. In the first instance, this suggests that spillovers of domestic R&D are more important than spillovers of foreign R&D. However, these two types of output elasticities cannot be compared directly, because manufacturing firms are overrepresented in the estimates with respect to the spillovers from industries. It is possible that manufacturing firms benefit to a greater extent from spillovers of outside R&D than firms in other industries (mainly services sectors) do, on average. This particularly holds in the case of knowledge spillovers (referring to the dissemination of technological knowledge, to be utilised in own innovations of firms) instead of ‘rent’ spillovers (referring to technological knowledge embodied in intermediate deliveries or capital goods, which leads to improving price-quality ratios for these inputs).[2]

Comparing subsequently the output elasticities of foreign R&D from individual firms or industries with those of foreign R&D at the macro level (the third group of results under ‘Type of spillovers’), limited differences appear. Here again a direct comparison is not appropriate, because of an overrepresentation of manufacturing firms and industries in the estimates with respect to international spillovers from firms or industries. Possibly, an upward effect of this overrepresentation of manufacturing on the estimates of the output elasticity at the micro and meso level is compensated largely by an effect in the opposite direction of difficulties in the measurement of the relevant outside R&D from foreign individual firms or industries. At the macro level only weights for countries are needed in order to calculate foreign outside R&D. At the micro and meso level also weights for industries or firms are required, which amplifies the chances of underestimation of the output elasticity of outside R&D.

In the next section of Table 6.1 it appears that no significant effects (at 5% level) and partly counter-intuitive signs of coefficients are found for the distinction between G7 and non-G7 countries. Theoretically, larger spillovers of domestic R&D and smaller spillovers of foreign R&D can be expected in G7 countries, simply as a result of the larger size of G7 countries in case of domestic spillovers and the smaller size of the world abroad for G7 countries in case of international spillovers. This theoretical reasoning is empirically confirmed by the significant positive G7 effect on output elasticities of domestic R&D at the macro level, found in the meta-analyses of the output elasticities of own R&D in Section 5. Furthermore, it is in line with the results of several macro studies in which the import share contributes to the explanation of TFP as interaction term for the output elasticity of foreign R&D (studies in the tradition of Coe and Helpman, 1995). The import share is related negatively to the (relative) size of a country. In Table D.1 of Appendix A, in one of the meta-regressions with a control for possible publication bias a significant negative G7 effect is found on the output elasticity of foreign outside R&D. This effect is present in the random effects estimate with equal weights for each study. In the regressions without a control for possible publication bias (presented in Table 6.1) a weakly significant negative effect is found for this particular estimate. All in all, it can be concluded that the distinction between G7 and non-G7 countries delivers results for the explanation of output elasticities of outside R&D that are mainly difficult to interpret in a theoretical sense and also in the context of empirical studies that show a positive G7 effect on the output elasticity of domestic R&D and a positive effect of the import share on the output elasticity of foreign R&D.

Under the heading of ‘Transmission channels for spillovers’ significant positive results are obtained for technological proximity and geographical proximity as transmission channels, compared to trade (baseline). For technology flows the results are significantly negative, but combined with trade also significant positive results are obtained for technology flows. This suggests that transmission channels that go beyond trade as a computationally relatively easy weighting mechanism lead to stronger output elasticities of outside R&D. Nonetheless, the results also suggest that trade has complementary explanatory power in the case of technology flows.

For the other explanatory factors in Table 6.1 various significant and insignificant results appear. It is difficult to assess the plausibility of all these estimates, because they are not directly related to spillovers of outside R&D. To some extent the results are in line with those of the meta-analysis of own R&D at the three levels together, but there are also large differences. However, the results in the latter analysis are not a good reference, because several of these are counter-intuitive or otherwise difficult to interpret. Furthermore, it is possible that the results for output elasticities of own R&D and those for output elasticities of outside R&D are to some extent communicating vessels.

[2] See, for example, Hall, Mairesse and Mohnen (2009) for a further description of these two categories of spillovers.

Table 6.1 Estimation results of meta-analysis for output elasticities of outside R&D; all data levels

	OLS, basic		**OLS, with equal weights for each study**		**Random effects, basic**		**Random effects, with equal weights for each study**	
	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic
Constant	0.215	2.14	0.259	1.87	0.287	2.45	0.372	2.71
Type of R&D spillovers (reference: international, macro level)								
Domestic, from individual firms								
- Intrasectoral	–0.154	–2.50	–0.110	–1.06	–0.128	–1.45	–0.134	–1.56
- Intersectoral	–0.329	–5.33	–0.285	–2.73	–0.367	–4.19	–0.374	–4.31
- Intrasectoral and intersectoral combined	–0.109	–1.08	0.275	0.88	–0.146	–1.64	0.127	0.47
Domestic, from industries								
- Intrasectoral	0.012	0.06	0.227	0.83	Collinearity; variable coincides with 'Value added'[*]			
- Intersectoral	0.155	1.51	–0.054	–0.40	0.124	1.08	–0.034	–0.31
- Intrasectoral and intersectoral combined	0.419	3.13	0.813	2.43	0.410	3.08	0.699	2.59
International, from individual firms or industries								
- Intrasectoral	0.050	0.81	0.039	0.55	0.055	1.02	0.069	1.16
- Intersectoral	0.121	2.34	0.124	2.46	0.100	1.93	0.088	1.78
- Intrasectoral and intersectoral combined	0.141	1.26	–0.063	–0.52	0.109	1.29	–0.002	–0.02
Effect of G7 (reference: non-G7 countries or country)								
G7 countries or country, domestic spillovers	0.153	0.88	–0.134	–0.60	0.215	1.24	–0.187	–0.73
G7 and non-G7 countries combined, domestic spillovers	–0.043	–1.12	–0.070	–0.87	–0.033	–0.95	–0.043	–0.72
G7 countries or country, international spillovers	–0.072	–0.94	–0.093	–1.13	–0.125	–0.97	–0.234	–1.82
G7 and non-G7 countries combined, international spillovers	0.004	0.17	–0.008	–0.17	–0.010	–0.12	–0.058	–0.67
Transmission channel for spillovers (reference: trade)								
Technological proximity	0.334	4.42	0.296	2.85	0.333	3.72	0.316	3.16
Technology flows	–0.156	–2.87	–0.195	–2.18	–0.146	–2.30	–0.181	–2.08
Technological proximity and trade combined	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Technology flows and trade combined	0.079	0.75	0.203	2.68	0.102	1.58	0.187	3.97
Geographical proximity	0.157	24.25	0.157	18.57	0.181	15.11	0.181	15.11
Foreign direct investment	–0.022	–3.48	–0.022	–2.54	0.002	0.18	0.002	0.19
None specified	0.013	0.24	0.043	0.96	0.010	0.20	0.037	1.07

Table continues on next page.

Table 6.1 (continued) Estimation results of meta-analysis for output elasticities of outside R&D; all data levels

	OLS, basic		**OLS, with equal weights for each study**		**Random effects, basic**		**Random effects, with equal weights for each study**	
	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic
Private or public outside R&D, at macro level (reference: private outside R&D)								
Public outside R&D	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Total outside R&D (i.e. private and public outside R&D)	0.044	1.04	0.044	1.35	Collinearity; variable coincides with 'Mean group estimate'**			
Input measurement of outside R&D (reference: R&D capital, 10 to 20% depreciation rate of R&D capital, no specific R&D deflator)								
R&D expenditure	Collinearity; variable coincides with R&D spillovers type 'Domestic, from industries, intrasectoral'*				Collinearity; variable coincides with 'Value added'*			
Depreciation rate of R&D capital:								
- less than 10%	–0.128	–1.40	–0.159	–1.51	–0.170	–2.77	–0.203	–3.80
- 20% or more	0.003	0.08	–0.013	–0.26	Collinearity; variable coincides with 'Mean group estimate'**			
Specific R&D deflator	0.030	0.66	0.013	0.25	0.010	0.21	0.001	0.02
Output measurement (reference: total factor productivity)								
Value added	0.300	1.68	0.309	1.59	0.383	1.37	0.682	2.02
Sales or gross production	0.134	0.68	0.029	0.12	0.161	1.04	0.215	1.85
Labour productivity***	0.123	1.52	0.117	1.21	0.180	2.30	0.214	2.83
Partial productivity	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Production function characteristics (reference: human capital not implemented in regression, in case of sales or gross output as output measure (directly or within a productivity measure) intermediate inputs not taken into account, constant returns to scale in factor inputs imposed, in case of domestic spillovers foreign R&D spillovers taken into account, no correction for double counting of own R&D)								
Human capital in regression	0.023	0.47	0.025	0.48	0.016	0.27	0.024	0.43
In case of sales or gross output as output measure (directly or within a productivity measure): intermediate inputs taken into account	0.116	2.40	0.135	5.39	0.224	1.17	0.334	4.56
Constant returns to scale not imposed	–0.377	–2.12	–0.369	–1.83	–0.467	–3.43	–0.532	–4.18
In case of domestic spillovers foreign R&D spillovers not taken into account	–0.013	–0.17	–0.046	–0.49	–0.054	–0.64	0.036	0.75

Table continues on next page.

Table 6.1 (continued) Estimation results of meta-analysis for output elasticities of outside R&D; all data levels

	OLS, basic		**OLS, with equal weights for each study**		**Random effects, basic**		**Random effects, with equal weights for each study**	
	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic
Production function characteristics, continued								
In case of private outside R&D: also outside public R&D taken into account	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
In case of public outside R&D: also outside private R&D taken into account	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Correction for double counting of own R&D	–0.039	–0.56	–0.030	–0.33	–0.054	–0.53	–0.063	–0.62
Estimation characteristics (reference: panel, fixed effects, homogeneity of output elasticity, estimation in levels, lagged R&D input, no time dummies or time trend included in regression)								
Cross-sectional or totals estimates	–0.246	–2.32	–0.259	–2.49	–0.249	–2.02	–0.248	–2.15
Random effects (level or growth estimate)	0.194	6.79	0.212	6.01	0.176	5.10	0.166	5.23
Mean Group Estimate / heterogeneous panel estimate (level estimate)****	–0.166	–5.58	–0.157	–6.18	–0.165	–3.72	–0.177	–9.10
Growth estimate	–0.133	–2.84	–0.081	–1.19	–0.127	–2.67	–0.069	–1.02
In case of growth estimate: long differences	–0.449	–5.71	–0.478	–4.79	–0.406	–2.79	–0.414	–3.18
Unlagged R&D input in case of level estimate	–0.009	–0.28	0.022	0.44	–0.010	–0.28	–0.028	–0.70
Unlagged R&D input in case of growth estimate	0.253	4.79	0.288	2.44	0.289	5.10	0.252	2.81
Time dummies or time trend included in level estimate	–0.036	–0.42	–0.024	–0.20	–0.103	–0.97	–0.130	–1.16
Time dummies or time trend included in growth estimate	–0.280	–3.70	–0.286	–2.63	–0.344	–3.18	–0.403	–3.28
Estimation method (reference: Ordinary Least Squares (OLS))*****								
Dynamic OLS (DOLS)	0.012	0.51	0.005	0.10	–0.002	–0.09	–0.018	–0.33
Fully Modified OLS (FMOLS) or Engle-Granger-Yoo three step procedure	0.075	1.57	0.006	0.17	0.076	1.60	–0.001	–0.01
Difference Generalized Method of Moments (GMM-DIF) or System Generalized Method of Moments (GMM-SYS)******	0.179	13.82	0.162	4.44	0.100	3.53	0.071	0.77
Two-Stage or Three-Stage Least Squares (2SLS or 3SLS)	–0.034	–1.42	–0.051	–1.88	–0.023	–1.08	–0.022	–1.62
Other (residual category): Feasible Generalized Least Squares (FGLS) or Seemingly Unrelated Regression (SUR)	–0.098	–4.03	–0.119	–3.73	–0.091	–3.71	–0.097	–4.20
Sectors (reference: no distinction)								
High tech	0.121	1.38	0.214	1.58	0.029	0.45	0.054	0.58
Medium tech	0.049	1.10	0.077	1.18	0.052	0.80	0.050	0.70
Low tech	–0.045	–0.93	–0.020	–0.27	–0.082	–1.59	–0.085	–1.44
Medium and low tech combined	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

Table 6.1 (continued) Estimation results of meta-analysis for output elasticities of outside R&D; all data levels

	OLS, basic		**OLS, with equal weights for each study**		**Random effects, basic**		**Random effects, with equal weights for each study**	
Number of observations	387		387		358		358	
R^2	0.390		0.470		0.712		0.720	
Additional estimate with the standard error of the output elasticity included as explanatory variable, in the context of possible publication bias (only estimation results for the standard error and the constant are shown, together with the R^2 and the number of observations):								
Standard error of coefficient	1.022	6.35	1.460	4.76	1.331	3.36	1.534	4.17
Constant	0.291	2.88	0.335	2.45	0.270	2.35	0.355	2.95
Number of observations	358*******		358*******		358		358	
R^2	0.462		0.607		0.737		0.762	

* Perfect collinearity, caused by coincidence of characteristics in the study by Rogers (2010).

** Perfect collinearity, caused by coincidence of characteristics in the study by Ang and Madsen (2013).

*** No capital productivity available in observations for output elasticities of outside R&D.

**** In case of random effects estimates no heterogeneous panel estimate available in observations at all three data levels.

***** No Generalized Least Squares (GLS) and Weighted Least Squares (WLS) estimates available in observations for output elasticities of outside R&D.

****** In case of random effects estimates no System Generalized Method of Moments (GMM-SYS) estimate available in observations at all three data levels.

******* Limited by availability of standard errors for coefficients. Therefore, the number of observations is the same here as in the case of random effects estimates.

Notes (general):

- The *t* statistics are based on cluster robust standard errors.
- The standard errors of the observations used in the random effects estimates are constrained to a minimum value of 0.002. This has hardly any effect on the results.

Since a clear picture of the role of the variables that are not directly related to spillovers is not achieved, one can wonder about the usefulness of including all these variables in the meta-analysis. As a sensitivity check, additional meta-regressions have been carried out with only the explanatory factors directly related to spillovers included. The results are shown in Tables D.2 and D.3 of Appendix D. The estimates in Table D.2 abstract from possible publication bias, whereas the estimates in Table D.3 contain the standard error of the coefficient as an additional explanatory variable in order to control for possible publication bias. In these estimates the results under the headings of 'Type of R&D spillovers' and 'Effect of G7' are broadly similar to those with the full list of explanatory variables. The results under 'Transmission channel for spillovers' are strongly different. The only transmission channel for which a robust significant effect is found (relative to trade as reference) in the alternative estimates, is geographical proximity. The foundation of this result is not particularly strong, because this transmission mechanism is only present in one observation from Ang and Madsen (2013).[3]

From the results of the meta-regressions for output elasticities of outside R&D it can be concluded that an unclear picture has appeared. The reason for this may be the large variation in estimation results in the studies used for the meta-analysis. The results of the meta-regressions show that this variation can be attributed only partly to different types of spillovers (domestic versus international and the other distinctions shown under 'Type of spillovers' in the tables). After controlling for these different types of spillovers, a lot of variation remains. It is questionable to what extent the residual variation can be explained in a plausible way on the basis of other study characteristics.

Probably the most informative results are the estimated values of the constant term, referring to a reference path with international spillovers at the macro level and with trade as transmission channel for the spillovers. In the estimates with only explanatory variables directly related to spillovers included, the values of the constant term are much lower than in the estimates with all explanatory variables included. The first-mentioned estimates are indicative of average results for output elasticities of outside foreign R&D in studies at the macro level. They vary from 0.083 to 0.170 in the estimates without a control for possible publication bias and from 0.076 to 0.145 in the estimates with a control for possible publication bias. In the case of the preferable random effects estimates they vary from 0.100 to 0.170.

7. Best guess estimates of the output elasticity of domestic R&D at the macro level

On the basis of the results of the meta-analyses for output elasticities in Tables 5.1 and 5.2 'best guesses' can be calculated for the output elasticity of domestic R&D in a country. This concerns the output elasticity of own R&D at the macro level, in which effects of domestic spillovers between firms and industries are automatically included. We focus in his context on the effects of characteristics that are present in the macro studies used for the meta-analyses. Furthermore, non-G7 counties are chosen as the reference. We first discuss which study characteristics we prefer.

For input measurement the R&D capital approach seems to be the best choice as it reflects the build-up of a stock of technological knowledge. We combine this with a depreciation rate of 10 to 20% for R&D capital, which covers the 15% depreciation rate that is most often used in empirical research (Griliches, 2000, p. 54). Furthermore, on theoretical grounds we prefer a specific R&D deflator for the calculation of the volume of R&D expenditure, as input for R&D capital.

For output measurement we choose total factor productivity, which is most commonly used in empirical studies at the macro level. Connected to this, no correction for double counting is assumed within input measurement. Also, constant returns to scale in the factor inputs labour and capital are assumed. The output elasticity of domestic R&D capital then has to be interpreted as representing extra returns of R&D, above the normal returns on traditional inputs of capital and labour. This can be

[3] Incidentally, also the (non-significant) result for foreign direct investment as transmission mechanism is based on only one observation from the study by Ang and Madsen (2003).

regarded as a result of domestic spillovers of R&D and, to a lesser extent, as a remuneration for above-normal financial risks that companies have to take with R&D projects.[4] Further production function characteristics in our preferred specification are: inclusion of human capital and international R&D spillovers as explanatory factors and taking into account private and public R&D together. Otherwise substantial bias in the output elasticities can be expected because of omitted variables.

The best type of data is obviously panel data. A specification in levels, with panel data and fixed effects are preferred estimation characteristics. First differencing disregards information on the long term relationship between R&D and productivity. Therefore, we prefer estimates in levels. Fixed effects prevent bias as a result of unobserved heterogeneity in the characteristics of countries, industries or firms in the samples. Furthermore, lagged R&D input and time dummies or a time trend can be preferred. A lag for R&D input takes into account that it takes some time before R&D investment has an effect on output.[5] Time effects capture common factors that vary over time, for example exogenous technological change and the state of the business cycle. In case of level estimates co-integrated equations are required to avoid spurious correlation. For estimating co-integrated equations, dynamic OLS (DOLS) is preferred as estimation method. DOLS adds lags and leads of the first differences of the regressors to control for endogeneity, apart from calculating standard errors that are robust to serial correlation in the residuals.

Furthermore, for the meta-analysis itself random effects estimates are chosen as the preferred estimation method. We present calculations based on estimation results with 'basic' random effects, in which all observation have the same weight, and calculations based on random effects with equal weights for each study. A slight preference may be given to the latter variant.

'Best guess' estimates are presented in the first columns of the right-hand side of Table 7.1 on the basis of meta-regression coefficients for studies at the macro level and in the columns further to the right on the basis of meta-regression coefficients for studies at the macro, meso and micro level together. The coefficients differ considerably between these two approaches. In the text below we will focus on the results from meta-regressions based on random effects with equal weights for each study. The results on the basis of 'basic' random effects estimates are shown in Table 7.1 for informative and comparative purposes.

On the basis of the meta-regression coefficients for studies at the macro level a 'best guess' output elasticity of 0.058 results for private R&D capital. This means that 10% more private R&D capital would lead to approximately 0.6% more total factor productivity. The effect of public R&D capital is smaller. With a 'best guess' estimate of 0.033 for the output elasticity of public R&D capital 10% more public R&D capital would result in approximately 0.3% more total factor productivity. The latter estimate is much less 'hard', because of the small number of studies in which the effect of public R&D has been investigated and also diverging results in these studies.

'Best guesses' on the basis of meta-regressions for studies at the macro, meso and micro level together are more difficult to determine. In these meta-regressions strong positive coefficients were found for including time dummies or a time trend in the estimated equation. The sign of these coefficients is contrary to what could be expected on analytical grounds. Including these coefficients in the 'best guess' calculations results in an output elasticity of 0.111 in the case of private R&D capital and an output elasticity of 0.056 in the case of public R&D capital. In view of the partly implausible information used in the 'best guess' based on the macro, meso and micro level together, the 'best guesses' based on the studies at the macro level will be chosen as main 'best guesses'.

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4 See for a previous discussion of this issue Guellec and van Pottelsberghe de la Potterie (2004).

5 In empirical analyses with R&D capital a lag of 1 year is often used for the R&D input. In addition to direct lags for R&D input, lags for all variables are taken into account implicitly in estimates of long-term relationships in levels. Such estimates are part of cointegration analysis, in which gradual adjustments of the dependent variable to long-term equilibrium values are supposed.

Table 7.1 Calculations for 'best guess' estimates of the output elasticity of domestic R&D in non-G7 countries, based on the meta-analyses in Tables 5.1 and 5.2

	Results of meta-analysis based on macro studies only				**Results of meta-analysis based on studies at all three data levels**			
	Random effects, basic		**Random effects, with equal weights for each study**		**Random effects, basic**		**Random effects, with equal weights for each study**	
	Private R&D capital	Public R&D capital	Private R&D capital	Public R&D capital	Private R&D capital	Public R&D capital	Private R&D capital	Public R&D capital
Constant, representing the output elasticity if variables are on the reference path	0.112*	0.112*	0.114*	0.114*	0.093*	0.093*	0.085*	0.085*
Effects of deviations from reference path for calculation of best guess estimates:								
- Non-G7 countries or country (instead of G7 and non-G7 countries combined as reference), macro level	–0.016*	–0.016*	–0.014	–0.014	–0.019	–0.019	–0.015	–0.015
- Public R&D (instead of private R&D as reference)	-	–0.032*	-	–0.034*	-	0.045	-	0.030
- Specific R&D deflator (instead of no specific R&D deflator as reference)	0.008	0.008	0.000	0.000	0.025*	0.025*	0.026*	0.026*
- Human capital in regression (instead of human capital not implemented in regression as reference)	–0.023*	–0.023*	–0.031*	–0.031*	–0.015	–0.015	–0.018	–0.018
- In case of private R&D: also public R&D taken into account (instead of private and public R&D not taken into account together as reference)	–0.022	-	–0.004	-	–0.053	-	–0.030	-
- In case of public R&D: also private R&D taken into account (instead of private and public R&D not taken into account together as reference)	-	0.022	-	0.005	-	–0.100*	-	–0.115*
- Time dummies or time trend included in regression (instead of no time dummies or time trend included as reference) in level estimate	–0.010	–0.010	–0.017	–0.017	0.054*	0.054*	0.043*	0.043*
- Dynamic OLS (instead of OLS as reference) as estimation method	0.011	0.011	0.010	0.010	0.017	0.017	0.020	0.020
Total	*0.060*	*0.072*	*0.058*	*0.033*	*0.102*	*0.100*	*0.111*	*0.056*

* Significant at 5% level.

For G7 countries the ‘best guess’ estimate of the output elasticity of private R&D capital can be increased by 0.132 (= 0.118 + 0.014) on the basis of the estimation results of the meta-analysis at the macro level in Table 5.2 of Section 5. This results in a value of 0.190 (= 0.058 + 0.132) as ‘best guess’ for the output elasticity of private R&D capital in G7 countries. For the output elasticity of public R&D capital we avoid such a calculation, since the observations for G7 countries used in the meta-analyses relate almost entirely to output elasticities of private R&D capital.[6]

8. Conclusions

Meta-analyses were performed to analyse the variation of output elasticities of R&D. 1214 elasticities from 38 studies were used to assess the effects of study characteristics such as R&D measures, output measures, estimation characteristics, production function characteristics and spillover mechanisms. Separate analyses were carried out for output elasticities of own R&D and output elasticities of outside R&D. In the case of output elasticities of own R&D a distinction was made between three data levels of analysis: the macro, the meso and the micro level, with meta-analyses performed at the three levels together and the three levels separately. In the case of output elasticities of outside R&D an analysis was carried out at the three levels together.

The meta-analyses deliver many results that are difficult to interpret from a theoretical or an analytical perspective. This holds in particular for the meta-analysis carried out for output elasticities of outside R&D. Furthermore, the results of the meta-analyses for the output elasticities of own R&D diverge across the different levels of analysis. In several cases the results seem to represent differences in output elasticities between specific studies rather than general relations. This suggests that there are study properties outside the included explanatory variables that have a substantial influence on the results. This concerns heterogeneity between studies for which direct causes are not easy to be designated. Differences in datasets between studies could be part of the explanation. Also, for some explanatory variables limited numbers of observations are available. The results of the meta-analyses for those explanatory factors are dependent on the output elasticities in a few single studies.

Despite the unclear results for various explanatory factors, several substantive conclusions can be drawn with respect to the influence of study characteristics on the estimation results for output elasticities of own R&D in the international literature:

- The output elasticity of domestic R&D at the macro level is much higher in G7 countries than in non-G7 countries.
- The output elasticity of domestic R&D at the macro level is substantially higher for private R&D than for public R&D.
- A correction for double counting of R&D in the inputs of capital and labour has a substantial positive effect on the output elasticity of domestic private R&D (founded on studies at the micro level).
- The output measure (e.g. value added, sales or labour productivity) does not have a clear influence on the output elasticity of domestic R&D at the various data levels of analysis.
- Including human capital as production factor has a substantial negative effect on the output elasticity of domestic R&D (founded on studies at the macro level).
- Not imposing constant returns to scale in factor inputs in the production function has a substantial negative effect on the output elasticity of domestic private R&D (founded on studies at the micro level).
- Not taking into account international spillovers has a substantial positive effect on the output elasticity of domestic R&D (founded on studies at the macro level).

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[6] Only one of the observations for G7 countries relates to the effect of public R&D capital. This is an observation in the study by Khan and Luintel (2006). In the case of the random effects estimates (on the basis of observations for which standard errors of the estimated output elasticities are available) this number decreases even to 0.

- In the category ‘Estimation characteristics’ Mean Group Estimates lead to a much higher output elasticity of domestic R&D than traditional fixed effects estimates (founded on studies at the macro level).
- A substantial negative effect of growth estimates on the output elasticity of domestic R&D appeared in the case of Difference Generalized Methods of Moments (GMM-DIF) in estimates at the micro level. There is no evidence of systematic substantial effects of other estimation methods on the output elasticity of domestic R&D at the various levels of analysis, compared to Ordinary Least Squares (OLS) as reference. Support for an important role of endogeneity bias in OLS estimates did not appear.
- In high tech industries output elasticities are substantially higher than in low tech industries (founded on studies at the micro and the meso level).

Using the meta-analyses we calculated ‘best guess’ estimates for the output elasticities of domestic private and public R&D capital at the macro level. For domestic business R&D capital the ‘best guess’ estimate amounts to 0.06 for non-G7 countries. For domestic public R&D capital the ‘best guess’ of the output elasticity in non-G7 countries is 0.03. However, the latter estimate should be interpreted with caution, because the effect of public R&D has been investigated in only a small number of studies and results in these studies are diverging. For G7 countries the ‘best guess’ estimate of the output elasticity of domestic private R&D capital is 0.19.

The ‘best guess’ estimates of the effect of domestic private R&D capital on total factor productivity at the macro level express ‘above-normal’ returns on private R&D capital, which can predominantly be viewed as the result of domestic spillover effects of R&D between firm and industries. The effect of domestic public R&D capital is by definition a result of spillovers, in fact spillovers from research carried out in public knowledge institutes to firms. Besides spillover effects from domestic R&D capital, international spillovers from foreign R&D capital are important. The output elasticity of foreign private R&D capital can be estimated to be in a range from 0.100 to 0.170. This implies for non-G7 countries that the output elasticity of foreign private R&D capital can be supposed to be substantially higher than the output elasticity of domestic private R&D capital. In addition to spillovers from foreign private R&D capital, spillovers from foreign public R&D may contribute considerably to productivity in the domestic business sector. For the effect of foreign public R&D no observations are available in the studies used in the meta-analyses.

At the micro and meso level output elasticities of domestic R&D do not differ much from those at the macro level, on average. In the meta-analyses at the three levels together no significant effect was found of micro and meso estimates relative to the macro level as reference. However, in studies at the micro and meso level firms and industries with relatively high R&D expenditure in relation to output are overrepresented. In case of a relatively high value of the ratio between R&D expenditure and output a particular value of an output elasticity of domestic R&D translates into a much lower effect on productivity per euro R&D than in the case of a ratio between R&D expenditure and output that is applicable at the macro level.[7] Taking this in consideration, the similarity of output elasticities at the macro level compared to those at the micro and meso level confirm that spillovers between domestic firms and industries are very strong.

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[7] This is mathematically visible in relationship (A.9) in Appendix A, which shows the marginal productivity of R&D capital in a positive relation to the output elasticity of R&D capital and the ratio between output and R&D capital.

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Appendix A Rates of return versus output elasticities

In this study estimates of rate of return to R&D are not taken into account because output elasticities of R&D and rates of return to R&D are not directly comparable to each other. Elasticities can be transformed to rates of return with a few assumptions, but rates of return cannot directly be transformed to elasticities without strict simplifying assumptions. In this appendix the relationship between the elasticities approach and the rates of return approach is described.

Most studies that estimate rates of return assume a framework proposed by Terleckyj (1974). The framework starts with a Cobb-Douglas production function (equation (A.1)). In this production function *Y*, *K* and *L* are standard symbols for respectively output (in this case value added), capital input and labour input. Innovation depends on exogenous technological progress ($e^{\lambda t}$) and on R&D capital *RDC* through elasticity μ. Equation (A.2) is the growth rate equivalent of (A.1). This is rewritten to a relationship for TFP growth in equation (A.3). Equation (A.4) is a definition relationship for the output elasticity of R&D capital μ.

$$Y = Ae^{\lambda t} K^{\alpha} L^{1-\alpha} RDC^{\mu} \tag{A.1}$$

$$\frac{dY}{Y} = \lambda + \alpha \frac{dK}{K} + (1-\alpha)\frac{dL}{L} + \mu \frac{dRDC}{RDC} \tag{A.2}$$

$$\frac{dTFP}{TFP} = \frac{dY}{Y} - \alpha \frac{dK}{K} - (1-\alpha)\frac{dL}{L} = \lambda + \mu \frac{dRDC}{RDC} \tag{A.3}$$

$$\mu = \frac{\partial Y}{\partial RDC}\frac{RDC}{Y} \tag{A.4}$$

The next step is to substitute the elasticity definition (A.4) into the TFP growth rate function (A.3):

$$\frac{dTFP}{TFP} = \lambda + \frac{\partial Y}{\partial RDC}\frac{dRDC}{Y} \tag{A.5}$$

To transform equation (A.5) to an expression with the rate of return as component, equation (A.5) can be rewritten as follows:

$$\frac{dTFP}{TFP} = \lambda + \frac{\partial Y}{\partial RDC}\frac{RD - \delta\ RDC}{Y} = \lambda + \frac{\partial Y}{\partial RDC}\left(1 - \delta \frac{RDC}{RD}\right)\frac{RD}{Y} \tag{A.6}$$

In this equation the marginal productivity of R&D capital, denoted by $\frac{\partial Y}{\partial RDC}$, represents the gross rate of return to R&D capital. The term $\left(1 - \delta \frac{RDC}{RD}\right)\frac{RD}{Y}$ is a definition of net R&D expenditure relative to output. In this term δ is a fixed depreciation rate on R&D capital and *RD* denotes gross R&D expenditure. The term $\left(1 - \delta \frac{RDC}{RD}\right)$ adjusts gross R&D expenditure relative to output on the far right-hand side of equation (A.6) to net R&D expenditure relative to output by subtracting depreciation on existing R&D capital from gross R&D expenditure.

By using information on R&D capital relative to output time-varying gross rates of return can be derived from an empirical estimate of the output elasticity of R&D capital. Comparing equation (A.6) to equation (A.3) it follows that:

$$\mu \frac{dRDC}{RDC} = \frac{\partial Y}{\partial RDC}\left(1-\delta\ \frac{RDC}{RD}\right)\frac{RD}{Y} \tag{A.7}$$

This can be rewritten to:

$$\mu \frac{RD-\delta\ RDC}{RDC} = \frac{\partial Y}{\partial RDC}\left(1-\delta\ \frac{RDC}{RD}\right)\frac{RD}{Y} \iff \tag{A.8}$$

$$\frac{\partial Y}{\partial RDC} = \mu \frac{\dfrac{RD-\delta\ RDC}{RDC}}{\left(1-\delta\ \dfrac{RDC}{RD}\right)\dfrac{RD}{Y}} = \mu \frac{(RD-\delta\ RDC)\dfrac{1}{RDC}}{(RD-\delta\ RDC)\dfrac{1}{Y}} = \mu \frac{Y}{RDC} \tag{A.9}$$

This shows that the gross rate of return to R&D capital is equal to the output elasticity of R&D capital multiplied by the ratio between output and R&D capital. The dependence of the gross rate of return to R&D capital on the ratio between output and R&D capital has a theoretical justification in supposed decreasing marginal returns to R&D capital, which is implied by assuming an output elasticity of R&D capital that is independent of the amount of R&D capital relative to output.

If an output elasticity is available from empirical research without annual data on output and R&D capital, but some information is available on gross R&D expenditure relative to output, it is possible to calculate a rough measure of the gross rate of return to R&D capital by assuming a fixed ratio between gross R&D expenditure and output and assuming furthermore a fixed growth rate for these two variables. The latter assumption makes it possible to derive a long-term relationship with a stable ratio between R&D capital and gross R&D expenditure.

Denoting the fixed growth rate by *g*, the development of gross R&D expenditure can be shown as follows:

$$\frac{dRD}{RD} = g \iff RD_{t+1} - RD_t = g\ RD_t \iff RD_{t+1} = (1+g)\ RD_t \tag{A.10}$$

This implies:

$$RD_t = \frac{RD_{t+1}}{1+g} \tag{A.11}$$

For the development of R&D capital the following relationship can be written:

$$dRDC = RD - \delta\ RDC \iff RDC_{t+1} = RD_t + (1-\delta)\ RDC_t \tag{A.12}$$

Substituting (A.11) in the equation on the right-hand side of (A.12) results in:

$$RDC_{t+1} = \frac{RD_{t+1}}{1+g} + (1-\delta)\ RDC_t \tag{A.13}$$

By deleting the subscripts for time periods a long-term relationship between *RDC* and *RD* can be derived:

$$RDC = \frac{RD}{(1+g)} + (1-\delta)\ RDC \iff RDC = \frac{RD}{\delta\ (1+g)} \tag{A.14}$$

An asterisk can be added as superscript to *RDC* in order to express that this variable denotes a long-term equilibrium value of *RDC* in this case:

$$RDC^{*} = \frac{RD}{\delta\,(1+g)} \tag{A.15}$$

Implementing this in (A.9) results in a long-run equilibrium relationship for the gross rate of return, in this case interpreting the gross rate of return as long-term equilibrium value (indicated by an asterisk as superscript for this variable):

$$\left(\frac{\partial Y}{\partial RDC}\right)^{*} = \mu \frac{Y}{\left(\frac{RD}{\delta\,(1+g)}\right)} = \mu \frac{\delta\,(1+g)}{\left(\frac{RD}{Y}\right)} \tag{A.16}$$

In empirical research in which rates of return to R&D capital are estimated directly, it is common to abstract from depreciation of R&D capital. This is done by technically assuming that the depreciation rate on R&D capital is 0. In that case the change in R&D capital (*dRDC*) in equation (A.5) is treated as equal to gross R&D expenditure and equation (A.6) for the TFP growth simplifies to:

$$\frac{dTFP}{TFP} = \lambda + \frac{\partial Y}{\partial RDC}\frac{RD}{Y} \tag{A.17}$$

Next, in this kind of empirical research it is assumed that the rate of return to R&D capital is a fixed parameter ρ. This yields:

$$\frac{dTFP}{TFP} = \lambda + \rho \frac{RD}{Y} \tag{A.18}$$

Most studies with the rate of return to R&D as empirical focus use this equation or a similar specification to estimate the relation between R&D and productivity. The assumption of zero depreciation can be considered as unrealistic and therefore as an important limitation of the rates of return approach. On the other hand, the elasticities approach implies an arbitrary assumption on the level of the depreciation rate. Treating the marginal productivity as a fixed parameter is another limitation of the rates of return approach. The elasticity approach implicitly assumes decreasing returns to scale in R&D capital (assuming an output elasticity of R&D capital < 1).

Particularly the assumption of zero depreciation makes results from this rate of return approach fundamentally different from the elasticities approach. They can be transformed relatively easily to elasticities estimates only when the zero depreciation rate is maintained as assumption. Then the output elasticity of R&D capital can be derived by multiplying the estimated rate of return by R&D expenditure relative to output (see equation (A.17)). Otherwise an assumption for the R&D depreciation rate has to be implemented in the calculation, in combination with calculations related to this concerning the ratio between R&D capital and R&D expenditure (see equation (A.6)). It has to be noted, however, that also with strong efforts in that direction, estimates of output elasticities based on the assumption of depreciation of R&D capital will be biased and internally inconsistent if the rates of return were estimated with the zero depreciation assumption for R&D capital. Finally, it has to be recalled that the assumption of a fixed parameter for the rate of return is a limitation in empirical estimates of rates of return. This can lead to further bias in transformations of estimated rates of return to output elasticities. Moreover, it leads to further technical complications in such calculations.

Besides the mentioned limitations of the rates of return approach in empirical estimates, an advantage of this method is that it is easier to take account of differences in output elasticities of R&D capital between firms or industries, dependent on technological opportunities in individual firm or industries. These differences in technological opportunities lead to differences in R&D expenditure relative to value added on the basis of cost-benefit considerations in firms. The assumption of a given (undifferentiated) output elasticity of R&D capital for all firms and industries implies that the marginal productivity of R&D capital in firms an industries with a relatively low R&D intensity (ratio between R&D expenditure and value added) is supposed to be (much) higher than in firms and industries with a relatively high RD intensity. In equation (A.9) this is visible, albeit on the basis of R&D capital relative to value added instead of R&D expenditure relative to value added. In reality, the marginal productivity of R&D capital may be roughly the same across firms or industries. Assuming indifferent rates of return to R&D capital between firms and industries implies that output elasticities of R&D capital are lower in firms or industries with a relatively low R&D intensity than in firms or industries with a relatively high R&D intensity.

Appendix B Studies used in the meta-analyses

B.1 Micro level studies

Characteristics of the micro level studies used in the meta-analyses are summarized in Table B.1. Subsequently, Table B.2 provides specific information on R&D spillover mechanisms in the micro level studies where R&D spillovers are included.

Basic specification
All micro level studies use the Cobb-Douglas specification in equations (1)-(3) of Section 2 of the main text.

Output measures
Studies at the micro level have a high variety in output measures. In the production function presented in equations (1)-(3) of Section 2 value added is used as dependent variable. Gross output and sales are other output measures used in the studies.

To derive an equation for labour productivity, equation (2) of Section 2 can be rewritten as follows:

$$\ln(Y/L)_{i,t} = \ln(A_{i,t}) + \alpha \ln(K/L)_{i,t} + \mu \ln(RDC/L)_{i,t} + (\alpha + \beta + \mu - 1)\ln(L_{i,t}) \qquad \text{(B.1)}$$

The value of $\alpha + \beta + \mu - 1$ can be estimated as a separate coefficient. If this value is greater (smaller) than 1, then increasing (decreasing) returns to scale apply. Similarly, an equation for capital productivity can be derived.

Partial productivity is used sometimes to control for a dependence of labour input on output. Equation (2) of Section 2 can be rewritten to the following equation for partial productivity:

$$\ln(Y_{i,t}) - \beta \ln(L_{i,t}) = \ln(A_{i,t}) + \alpha \ln(K_{i,t}) + \mu \ln(RDC_{i,t}) \qquad \text{(B.2)}$$

In this equation a value for β has to be chosen beforehand, in order to make it possible to estimate values for the parameters α and μ. This value can be based on the share of labour income in total output. Under the assumption of perfect competition on product markets it can be derived that the output elasticity of labour input is equal to the labour income share (see, e.g., Solow (1957)). The average labour income share for all individual firms in the sample period can be used, but also firm-specific values. Hall and Mairesse (1995) use both methods. In the micro level studies used in the meta-analyses, labour productivity and partial productivity are defined on the basis of value added as well as sales. Wang and Tsai (2004) use capital productivity as the output measure, where it is defined as value added per unit of physical capital.

If gross output or sales is used as output measure, directly or as a component in productivity, it matters whether or not intermediate inputs are included as a separate production factor in the production function. Because of data limitations, intermediate inputs are often omitted in such estimates. These data limitations are also a reason that several micro studies use sales as output measure and not value added. For example, micro level data for firms in the US are often extracted from the Compustat database, which contains data on sales, but not on intermediate inputs and, as a consequence, neither on value added. If intermediate inputs are not taken into account, output elasticities of R&D capital are, however, roughly comparable to those obtained in estimates with value added as output measure. Considered from a time series perspective, the development of sales and gross output is to a large extent similar to the development of value added. Viewed in the cross-section dimension, relative differences between firms in sales or gross output are to a large extent comparable to relative differences in value added. This implies that value added can represent gross output or sales in empirical estimates quite well. Estimation of a separate contribution of intermediate inputs to the development or the level of gross output or sales leaves less explanation for the contribution of other

Table B.1 Characteristics of micro studies used in the meta-analyses

Study	Output measurement (dependent variable)	Input measurement			Estimates in levels or in growth?	Characteristics of estimates in levels		Estimation method(s) used
		R&D capital or R&D expenditure?	Specific R&D deflator?	Correction for double counting of R&D?		With respect to treatment of fixed effects	Time dummies or time trend included?	
Bartelsman et al. (1996)	- Value added - Gross output* - Partial productivity (based on value added)	- R&D capital - R&D expenditure	Yes	In most of the estimates	- Levels - Growth (long differences)	Cross-sectional estimates for separate years	No	- OLS - WLS
Bloom et al. (2013)	Sales**	R&D capital	No	No	Levels	- 'Total estimates' - Fixed effects dummies included	Time dummies included	- OLS - 2SLS
Branstetter (2001)	Sales***	R&D capital	No	No	Growth (long differences)	-	-	OLS
Capron and Cincera (1998)	Sales**	R&D capital	No	No	- Levels - Growth	'Within' estimates	Time dummies included	- OLS - GMM-DIF
Cuneo and Mairesse (1984)	Labour productivity (based on value added and, as alternative, on sales***)	R&D capital	No	In almost all estimates	Levels	- 'Total estimates' - 'Within' estimates	Time trend included	OLS
Griliches (1986)	- Value added - Partial productivity (based on sales**)	- R&D capital - R&D expenditure	Yes	In most of the estimates	- Levels - Growth (long differences)	Cross-sectional estimates for separate years	No	OLS
Griliches and Mairesse (1984)	Labour productivity (based on sales**)	R&D capital	No	No	Levels	- 'Total estimates' - 'Between estimates' - 'Within' estimates	Time dummies or time trend included	OLS
Hall (1993)	Sales**	R&D capital	Yes	No	- Levels - Growth (first and long differences)	'Total estimates'	Time dummies included	OLS
Hall and Mairesse (1995)	- Labour productivity - Partial productivity (both based on value added)	- R&D capital - R&D expenditure	No	In most of the estimates	- Levels - Growth (first and long differences)	- 'Total estimates' - 'Within' estimates	Time dummies included	- OLS - SUR

Table continues on next page.

Table B.1 (continued) Characteristics of micro studies used in the meta-analyses

Study	Output measurement (dependent variable)	Input measurement			Estimates in levels or in growth?	Characteristics of estimates in levels		Estimation method(s) used
		R&D capital or R&D expenditure?	Specific R&D deflator?	Correction for double counting of R&D?		With respect to treatment of fixed effects	Time dummies or time trend included?	
Harhoff (1998)	- Sales** - Labour productivity (based on sales**)	R&D capital	No	In almost all estimates	- Levels - Growth (differences varying from at least 2 years)	- 'Total estimates' - Fixed effects dummies	Time dummies included	OLS
Harhoff (2000)	Sales**	R&D capital	No	Yes	Growth (long differences)	-	Time dummies included	OLS
Los and Verspagen (2000)	Sales**	R&D capital	No	No	Levels	- 'Between estimates' - 'Within' estimates	No	- OLS - Engle-Granger-Yoo three step procedure
Mairesse and Hall (1996)	- value added - sales***	R&D capital	Yes for USA, no for France	In some estimates	- Levels - Growth (first differences)	- 'Total estimates' - 'Within' estimates	Time dummies included	- OLS - GMM-DIF
Ortega-Argilés et al. (2010)	Labour productivity (based on value added)	R&D capital	No	No	Levels	- 'Total estimates' - Random effects	Time dummies included	- OLS - FGLS
Rogers (2010)	Value added	R&D expenditure	No	No	Levels	'Total estimates'	Time dummies included	- OLS - 2SLS
Schankerman (1981)	Value added	R&D capital	No	In half of the estimates	Levels	Cross-sectional estimates for one year	No	OLS
Wang and Tsai (2004)	Capital productivity (based on value added)	R&D capital	Yes	Yes	Levels	Random effects	time dummies or time trend included	FGLS

* Intermediate inputs taken into account as separate input factor.
** Intermediate inputs not taken into account as separate input factor.
*** Intermediate inputs taken into account as separate input factor in part of the estimates.

Table B.2 R&D spillover mechanisms in micro studies used in the meta-analyses

Study	Spillovers from individual firms, industries or countries	Domestic: distinction between intrasectoral and intersectoral	International: distinction between intrasectoral, intersectoral and macro level	Transmission channel	Weights based on:
Bloom et al. (2013)	From individual firms (instead of countries or industries)	Combination of intrasectoral and intersectoral	-	Technological proximity	Degree of similarity between firms of the distribution of patents across technology classes (Jaffe's method and a so-called Mahalanobis extension)
Branstetter (2001)	From individual firms (instead of countries or industries)	Combination of intrasectoral and intersectoral	- Intrasectoral - Intersectoral	Technological proximity	Degree of similarity between firms of the distribution of patents across technology classes (Jaffe's method)
Capron and Cincera (1998)	From individual firms (instead of countries or industries)	- Intrasectoral - Intersectoral - Combination of intrasectoral and intersectoral	- Intrasectoral - Intersectoral - Combination of intrasectoral and intersectoral	Technological proximity	Degree of similarity between firms of the distribution of patents across technology classes (Jaffe's method)
Harhoff (2000)	From individual firms (instead of countries or industries)	Combination of intrasectoral and intersectoral	-	Technological proximity	Degree of similarity between firms of the distribution of R&D across product areas
Los and Verspagen (2000)	From industries (instead of individual firms or countries)	Combination of intrasectoral and intersectoral	-	- Technology flows - None specified	- Knowledge flows between industries, based on information on technology classes in patent applications (Verspagen's method) - Product flows at industry level between producers and users of patented inventions (Yale patent matrix) - Not applicable (no weighting scheme) in case of no transmission channel specified
Rogers (2010)	From industries (instead of individual firms or countries)	Intrasectoral	-	None specified	Not applicable (no weighting scheme)

input factors, including R&D capital. This has a downward effect on the output elasticity of R&D capital. Whereas a better measurement of the effect of R&D capital on gross output or sales is achieved in this way, the output elasticity can no longer be interpreted as an approximation of the effect of R&D capital on value added. See for direct comparisons of estimates that confirm this line of reasoning Mairesse and Hall (1996), Cuneo and Mairesse (1984) and Bartelsman et al. (1996).

Input measurement
In most estimates at the micro level R&D capital is used as R&D input variable. In some studies R&D expenditure is used, solely or in a part of the estimates. In the long run R&D expenditure and R&D capital are closely connected to each other. A structural increase of the level of the volume of R&D expenditure by 1 percent relative to a baseline will result in 1 percent extra volume of R&D capital in the long run. This can easily be seen in the long-term equilibrium relationship between R&D expenditure and R&D capital presented as equation (A.14) in Appendix A.

Theoretically, R&D capital may be preferred as determinant of output and productivity over R&D expenditure, because R&D capital reflects knowledge accumulated over a long period of time. R&D expenditure can be used as a short-term proxy for R&D capital. In cross-sectional level estimates between firms (or industries or countries) it is a better proxy than in first difference growth estimates and other estimates in which the times series dimension plays an important role. In a more general sense the stability of the level of R&D expenditure or of the growth in it determines to what extent R&D expenditure is a good proxy for R&D capital.

In a part of the studies a specific R&D deflator is used for calculating the volume of R&D expenditure (as a direct explanatory variable or as input variable for R&D capital). This is done by taking a weighted average of a deflator for labour costs and a general price deflator for other R&D costs.

R&D expenditure is composed of labour, capital and material costs. Therefore, R&D expenditure is counted twice, unless labour, capital and intermediate inputs in the production function are cleared of their R&D parts. If no correction for this double counting of R&D takes place, the estimated output elasticity does not measure the full effect of R&D, but only extra returns on R&D beyond the normal returns on capital, labour and intermediate inputs. In several micro studies included in the meta-analyses no correction for double counting of R&D has been made. There are also various studies where a correction for double counting has been made in part of the estimates, sometimes with the specific aim to investigate the effect of double counting on the results.

Estimation characteristics
A core distinction is the difference between growth and level estimates. In case of growth estimates long differences can be distinguished from first differences. Using first differences it can be difficult to estimate relationships appropriately, because R&D effects can occur over more than one period. Long difference estimates over relatively long periods are to a certain extent comparable to level estimates, because both are particularly suitable for the estimation of long-term relationships between variables.

In case of level estimates specific attention has to be paid to individual specific effects. Not taking account of fixed effects can lead to bias in the estimated coefficients, if unobserved characteristics in the cross-section dimension are correlated to explanatory variables that are included in the regression (see, e.g., Verbeek, 2012, p. 374). The following types of estimates can be distinguished**:** cross-sectional estimates, ‘total estimates’, ‘within estimates’, fixed effects and random effects. In various studies more than one method is used. In some studies cross-sectional estimates have been carried out for separate years. In other studies ‘between estimates’ are presented, which are cross-sectional estimates on mean values over time in panel data. ‘Total estimates’ are panel estimates in which fixed effects are not taken into account.

Random effects estimates take a position in between ‘total estimates’ and ‘within estimates’. Whereas in ‘within estimates’ time averages are subtracted from the values of variables, in random effects estimates a fraction of the time averages is subtracted, dependent on the variances of the random effects error term and the residual (time-varying) error term and the number of time periods (see, e.g., Verbeek, 2012, pp. 381-384). Random effects estimates lead to unbiased results if the individual specific effects represented by the random effects are not correlated with the explanatory variables. A Hausman test (Hausman, 1978) can be used to investigate this. In the two studies in which the random effects method is used (Ortega-Argilés et al., 2010; Wang and Tsai, 2004), it is reported that the Hausman test was passed.

Particularly in case of level estimates it is relevant whether or not time dummies or a time trend is included. Time dummies or a time trend can control for relevant time-varying factors that are omitted in the explanatory variables**.** Not including time dummies or a time trend can lead to too much attribution to R&D. In most of the level estimates at the micro level time dummies are included. In some studies a time trend is used. It should be noted that time dummies or a time trend have a technical character, with no real economic factors visible behind them. It can be difficult to distinguish technical explanations for the development of the output variable by time dummies or a time trend from real economic factors such as R&D. If the development of the R&D variable is similar across firms, then time dummies, and, in case of a trend, a trend variable may function as a proxy for R&D. The effect of R&D could be underestimated in that case

Estimation methods
Most studies at the micro level use Ordinary Least Squares (OLS) as the estimation method. Bartelsman et al. (1996) apply Weighted Least Squares (WLS) in two long difference estimates explaining growth in value added. They weigh the variables by the square root of R&D capital, in order to conduct a robustness check for the effect of heteroskedasticity. Feasible Generalized Least Squares (FGLS) is the method applicable for random effects estimates. This method is used in the studies by Ortega-Argilés et al. (2010) and Wang and Tsai (2004). Two-Stage Least Squares (2SLS) is used by Bloom et al. (2013), who use tax credit components of the user cost of R&D to compute instruments for stocks of outside R&D capital (not for the stock of own R&D capital). Rogers (2010) uses lagged values of explanatory variables as instruments, among which a two year lag for the R&D variables. Capron and Cincera (1998) and Mairesse and Hall (1996) use the Difference Generalized Method of Moments (GMM-DIF) in a part of the estimates to control for endogeneity of R&D capital and other explanatory variables. This is done by using lagged values of explanatory variables in levels as instruments for variables denoted in first differences. Seemingly Unrelated Regression (SUR) is used by Hall and Mairesse (1995) in a simultaneous estimation of equations explaining labour input and value added in the context of the partial productivity approach. This technique takes account of correlation between the error terms in the separate equations, in order to improve the efficiency of the estimates. Los and Verspagen use the Engle-Granger-Yoo three step procedure (Engle and Yoo, 1991) in a cointegration analysis. With this technique ‘within estimates’ are modified on the basis of supplementary estimates with an error correction model, in order to obtain unbiased normally distributed estimates for long-term equilibrium relationships. This is applicable is case of non-stationary variables with the property of cointegration, which are both confirmed in tests conducted by Los and Verspagen (2000). Many estimates in levels with controls for fixed effects can be viewed from the cointegration perspective. Remarkably, within the studies at the micro level included in the meta-analyses, only Los and Verspagen (2000) pay attention to this issue. In the estimates of Los and Verspagen (2000) applying the Engle-Granger-Yoo three step procedure leads to much higher standard errors than in the conventional within estimates.

R&D spillovers
In a limited number of studies at the micro level spillover effects of outside R&D are estimated. Six micro studies included in our meta-analyses contain estimates of these spillover effects. The implementation of spillover variables in these studies vary. A general feature is, however, that stocks of outside R&D capital are included as explanatory variables in the equations. This can be weighted R&D capital stocks of other individual firms for which data are available, stocks of total R&D capital in the industry to which the firm belongs (Rogers, 2010) or weighted stocks of R&D capital in other industries as well as the industry to which the firm belongs (Los and Verspagen, 2000). This can result in measurements of intrasectoral spillovers, intersectoral spillovers or a combination of both.

Furthermore, a distinction is sometimes made between stocks of domestic outside R&D capital and stocks of foreign R&D capital.

Table B.2 shows the implementation of spillovers in the six micro level studies where they are included. Different weighting schemes are possible for the construction of the outside R&D capital stock. In the micro studies presented in Table B.2 the weighting is mostly based on ‘technological proximity’ as transmission mechanism for spillovers. This represents the degree of similarity between firms of the distribution of patents across technology classes (mainly based on Jaffe (1986)) or, as an alternative, the distribution of R&D across product areas.

B.2 Meso level studies

Characteristics of the meso level studies used in the meta-analyses are summarized in Table B.3. Table B.4 gives specific information on the modelling of R&D spillovers in the meso level studies where this is applicable.

Basic specification
Most meso level studies use an extended Cobb-Douglas production function in which R&D spillovers between industries are taken into account by including R&D capital in other domestic industries and often also R&D capital in industries abroad. Equation (B.3) shows an example of a specification of this kind, formulated as a logarithmic equation:

$$\ln(Y_{s,t}) = \ln(A_{s,t}) + \alpha \ln(K_{s,t}) + \beta \ln(L_{s,t}) + \mu_1 \ln(RDC_{own,dom_{s,t}}) + \mu_2 \ln(RDC_{other,dom_{s,t}}) + \mu_3 \ln(RDC_{own,for_{s,t}}) + \mu_4 \ln(RDC_{other,for_{s,t}}) \qquad \text{(B.3)}$$

where:

Y	= volume of value added at the industry level
A	= indicator for the level of technology at the industry level, to the extent that this is not explained by the R&D capital variables included in the equation
K	= volume of physical capital at the industry level
L	= volume of labour input at the industry level
$RDC_{own,dom}$	= volume of own industry’s R&D capital, domestic
$RDC_{other,dom}$	= volume of other industries’ R&D capital, domestic
$RDC_{own,for}$	= volume of own industry’s R&D capital, foreign
$RDC_{other,for}$	= volume of other industries’ R&D capital, foreign
s	= subscript denoting an individual industry
t	= subscript denoting an individual year

In equation (B.3) the parameter μ_1 is the output elasticity of R&D capital in the own domestic industry. The parameters μ_2, μ_3 and μ_4 are parameters for outside R&D capital in other domestic industries, R&D capital in the own industry abroad and R&D capital in other industries abroad. Taking first differences results in a growth equation, analogous to equation (3) in Section 2.

Verspagen (1995) uses a more complicated translog production function instead of a Cobb-Douglas production function as a framework for the estimation of output elasticities. In this case the output elasticities are flexible, dependent on the magnitudes of the inputs labour, physical capital and R&D capital. Verspagen (1995) presents estimation results for the output elasticities based on the sample means of the inputs. Only R&D capital in the own domestic industry is included in the specification. Therefore the study abstracts from spillovers from other industries. This also holds for the study by Ortega-Argilés et al. (2010).

Table B.3 Characteristics of meso studies used in the meta-analyses

Study	Output measurement (dependent variable)	Input measurement			Estimate in levels or in growth?	Characteristics of estimates in levels		Estimation method(s) used
		R&D capital or R&D expenditure?	Specific R&D deflator?	Correction for double counting of R&D?		With respect to treatment of fixed effects	Time dummies or time trend included?	
Braconier and Sjöholm (1998)	Total factor productivity (based on value added)	R&D capital	No	No	Growth (first differences)	-	-	OLS
Frantzen (2002)	Labour productivity (based on value added)	R&D capital	Yes	No	Levels	Fixed effects dummies	No	- OLS - DOLS
López-Pueyo et al. (2008)	Total factor productivity (based on value added)	R&D capital	No	No	Levels	Fixed effects dummies	No	- OLS - DOLS
Ortega-Argilés et al. (2010)	Labour productivity (based on value added)	R&D capital	No	No	Levels	- ‘Total estimates’ - Random effects	Time dummies included	- OLS - FGLS
Soete and ter Weel (1999)	Labour productivity (based on value added)	R&D capital	No	Yes	Levels	‘Within’ estimates	No	OLS
Verspagen (1995)	Value added	R&D capital	No	In half of the estimates	Levels	Fixed effects dummies	Time trend included	3SLS
Verspagen (1997)	Labour productivity (based on value added)	R&D capital	No	No	- Levels - Growth (first differences)	- ‘Between estimates’ - ‘Within’ estimates	No	OLS

Table B.4 R&D spillover mechanisms in meso studies used in the meta-analyses

Study	Spillovers from individual firms, industries or countries	Domestic: distinction between intrasectoral and intersectoral	International: distinction between intrasectoral, intersectoral and macro level	Transmission channel	Weights based on:
Braconier and Sjöholm (1998)	From industries (instead of individual firms or countries)	Intersectoral	- Intrasectoral - Intersectoral	None specified	Not applicable (no weighting scheme)
Frantzen (2002)	From industries (instead of individual firms or countries)	Intersectoral	- Intrasectoral - Intersectoral - Combination of intrasectoral and intersectoral	Combination of technology flows and trade	Methodology in accordance with Verspagen (1997) [see below]
López-Pueyo et al. (2008)	From industries (instead of individual firms or countries)	Intersectoral	- Intrasectoral - Intersectoral	Trade	- Bilateral imports (CH* and LP*) - Intermediate deliveries
Soete and ter Weel (1999)	From industries (instead of individual firms or countries)	Intersectoral	Combination of intrasectoral and intersectoral	Combination of technology flows and trade	Methodology in accordance with Verspagen (1997) [see below]
Verspagen (1997)	rom industries (instead of individual firms or countries)	Intersectoral	Combination of intrasectoral and intersectoral	Combination of technology flows and trade	For technology flows: - knowledge flows between industries, based on information on technology classes in patent applications (Verspagen's method) - product flows at industry level between producers and users of patented inventions (Yale patent matrix) For trade: - international: bilateral imports (CH*) - national: domestic output

* CH = Coe and Helpman approach: bilateral imports as share in total imports; LP = Lichtenberg and van Pottelsberghe de la Potterie approach: bilateral imports divided by value added.

Output measures
Studies at the meso level use various output measures as dependent variable. Labour productivity is most often used as dependent variable, in all cases based on value added as basic output variable. In two studies total factor productivity is used as output measure, also based on value added. These are the studies by Braconier and Sjöholm (1998) and López-Pueyo et al. (2008). In Verspagen (1995) the output measure is value added.

An equation for labour productivity has already been shown in the section on micro level studies (equation (B.1)). Total factor productivity is a measure of productivity that reflects how much value added is generated relative to total inputs of labour and physical capital. The weights of labour input and physical capital in the calculation of total factor productivity are based on their output elasticities. Assuming constant returns to scale with respect to the inputs of labour and physical capital ($\alpha + \beta = 1$), equation (B.3) can be rewritten as follows:

$$\begin{aligned}\ln(TFP_{s,t}) = \ln(Y_{s,t}) - \alpha \ln(K_{s,t}) - \beta \ln(L_{s,t}) = \ln(A_{s,t}) + \mu_1 \ln(RDC_{own,dom_{s,t}}) \\ + \mu_2 \ln(RDC_{other,dom_{s,t}}) + \mu_3 \ln(RDC_{own,for_{s,t}}) + \mu_4 \ln(RDC_{other,for_{s,t}})\end{aligned} \qquad \text{(B.4)}$$

where:
TFP = total factor productivity

As already noted in the section on micro level estimates, under the assumption of perfect competition on product markets the output elasticity of labour input is equal to the labour income share. Similarly, the output elasticity of physical capital is the capital income share under the assumption of perfect competition. In standard growth accounting analyses total factor productivity is calculated along these lines. This method has also been applied in the two (aforementioned) meso level studies used in the meta-analyses with total factor productivity as dependent variable. In both studies constant returns to scale are assumed with respect to the inputs of labour and physical capital.

In equation (B.4) the inputs labour and physical capital partly include labour input and physical capital used for R&D activities. As a result the elasticity of the R&D capital in the own domestic industry represents extra returns on R&D capital, above the normal returns on labour and physical capital used in the own domestic industry. Extra returns on R&D capital in the own domestic industry can largely be interpreted as a result of domestic intrasectoral spillovers. Besides these spillovers from R&D capital in the own domestic industry, spillovers from R&D capital in other domestic industries (domestic intersectoral spillovers), spillovers from R&D capital in the own industry abroad (international intrasectoral spillovers) and spillovers from R&D capital in other industries abroad (international intersectoral spillovers) can generate total factor productivity gains.

Input measurement
In all studies at the meso level included in the meta-analyses, R&D capital is used as input measure for R&D. The study by Frantzen (2002) is the only one in which a specific R&D deflator is used. Also in only one study a correction has been made for double counting of R&D. This is the study by Verspagen (1995), who shows for comparison results with a correction for double counting together with results without that correction.

Estimation characteristics
In the studies at the meso level a large majority of the estimates is based on regressions using level variables. Only in the study by Braconier and Sjöholm (1998) and in part of the regressions by Verspagen (1997) growth equations are estimated, in all cases formulated in first differences. In most of the estimates fixed effects are included or 'within estimates' performed. Verspagen (1997) presents both 'within estimates' and cross-sectional 'between estimates'. Ortega-Argilés et al. (2010) present 'total estimates' together with random effects estimates. In most level estimates at the meso level no time dummies or time trends are included. This differs from the frequent use of time dummies or a time trend in micro level estimates.

In the study by Verspagen (1997) the growth estimates are part of an error correction model, following the two step procedure developed by Engle and Granger (1987). Lagged residuals from estimates in levels together with first-difference growth variables are used to explain first-difference growth of the output variable. The estimates in levels are considered as estimates of long-term equilibrium relationships, whereas the error correction model estimates short-term dynamics, including movements to the long-term equilibrium via the coefficient for the lagged residuals from the estimates in levels. The coefficient for the lagged residuals also tests for cointegration of the equation estimated in levels. Cointegration is confirmed by the estimation results of Verspagen (1997) for the coefficient of the lagged residuals of the ('within') level estimates. In the studies by López-Pueyo et al. (2008) and Frantzen (2002) cointegration tests have also been conducted, with direct tests conducted on the residuals of fixed effects estimates. These tests also confirmed cointegration.

Estimation methods
Ordinary Least Squares (OLS) and Dynamic Ordinary Least Squares (DOLS) are the most common estimation methods in the studies at the meso level. Frantzen (2002) and López-Pueyo et al. (2008) use DOLS besides OLS in the context of cointegration regressions. OLS estimates of cointegrating equations have the drawback that their distribution is generally non-standard. This is due to finite sample bias, which may be caused by endogeneity of the explanatory variables and by serial correlation in the residual error term. Frantzen (2002) mentions specifically the endogeneity that can occur in OLS estimates due to a reverse linkage caused by a positive response of R&D spending to growth opportunities. In the DOLS estimates level variables are combined with leads and lags of first differences and unlagged first differences of the level variables to control for endogeneity. Standard errors are calculated by using a covariance matrix of errors that is robust to serial correlation. Feasible Generalized Least Squares (FGLS) is used by Ortega-Argilés et al. (2010 for their random effects estimates. Three-Stage Least Squares (3SLS) is applied by Verspagen (1995), with lagged values of the explanatory variables as instruments to control for endogeneity.

R&D spillovers
In five of the seven studies at the meso level spillovers of outside R&D capital are included. Table B.4 shows that effects of domestic intersectoral spillovers are measured together with effects of international spillovers. Within the latter intrasectoral and intersectoral spillover effects are estimated separately or as a combination. Across the estimates various weighting schemes are used for the construction of outside R&D capital, mostly based on technology flows and/or trade as transmission mechanisms for spillovers. The technology flow approach is an alternative for technological proximity. It focuses more directly on technology flows between producers and users of knowledge instead of potential use of technological knowledge dependent on technological proximity.

B.3 Macro level studies

Characteristics of the macro level studies used in the meta-analyses are summarized in Table B.5. In Table B.6 specific information is presented on the modelling of R&D spillovers in the macro studies where they are included.

Basic specification
At the macro level it is common to take a Cobb-Douglas production function with domestic and foreign R&D capital as a starting point. Equation (B.5) shows a logarithmic specification:

$$\ln(Y_{c,t}) = \ln(A_{c,t}) + \alpha \ln(K_{c,t}) + \beta \ln(L_{c,t}) + \mu_1 \ln(RDC_{dom_{c,t}}) + \mu_2 \ln(RDC_{for_{c,t}}) \tag{B.5}$$

where:
Y = volume of value added at the macro level
A = indicator for the level of technology at the macro level, to the extent that this is not explained by the R&D capital variables included in the equation
K = volume of physical capital at the macro level
L = volume of labour input at the macro level

Table B.5 Characteristics of macro studies used in the meta-analyses

Study	Output measurement (dependent variable)	Input measurement			Estimate in levels or in growth?	Characteristics of estimates in levels		Estimation method used
		R&D capital or R&D expenditure?	Specific R&D deflator?	Correction for double counting of R&D?		With respect to treatment of fixed effects	Time dummies or time trend included?	
Ang and Madsen (2013)	Total factor productivity (based on value added)	R&D capital (total of business and public R&D capital)	Yes	No	Levels	Mean group estimates	No	DOLS
del Barrio-Castro et al. (2002)	Total factor productivity (based on value added)	R&D capital (business R&D capital)	Yes	No	Levels	Fixed effects dummies	No	- OLS - DOLS
Coe and Helpman (1995)	Total factor productivity (based on value added)	R&D capital (business R&D capital)	Yes	No	Levels	Fixed effects dummies	Time dummies in a few estimates	OLS
Coe et al. (2009)	Total factor productivity (based on value added)	R&D capital (business R&D capital)	No	No	Levels	- Fixed effects dummies - Mean group estimates	No	DOLS
Edmond (2001)	Total factor productivity (based on value added)	R&D capital (business R&D capital)	Yes	No	Levels	- Fixed effects dummies - Mean group estimates	No	OLS
Engelbrecht (1997)	Total factor productivity (based on value added)	R&D capital (business R&D capital)	Yes	No	- Levels - Growth (first differences and long differences)	Fixed effects dummies	No	- OLS - GLS
Frantzen (2000)	Total factor productivity (based on value added)	R&D capital (business R&D capital)	Yes	No	- Levels - Growth (first differences)	Fixed effects dummies	No	- OLS - DOLS
Funk (2001)	Total factor productivity (based on value added)	R&D capital (business R&D capital)	Yes	No	Levels	Fixed effects dummies	No	- OLS - FMOLS - DOLS

Table continues on next page.

Table B.5 (continued) Characteristics of macro studies used in the meta-analyses

Study	Output measurement (dependent variable)	Input measurement			Estimate in levels or in growth?	Characteristics of estimates in levels		Estimation method used
		R&D capital or R&D expenditure?	Specific R&D deflator?	Correction for double counting of R&D?		With respect to treatment of fixed effects	Time dummies or time trend included?	
Guellec and van Pottelsberghe de la Potterie (2004)	Total factor productivity (based on value added)	R&D capital (business R&D capital and public R&D capital)	No	No	- levels - growth (first differences)	Fixed effects dummies	Time dummies, except in one estimate	- SUR - 3SLS
Kao et al. (1999)	Total factor productivity (based on value added)	R&D capital (business R&D capital)	Yes	No	Levels	Fixed effects dummies	No	- OLS - FMOLS - DOLS
Keller (1998)	Total factor productivity (based on value added)	R&D capital (business R&D capital)	Yes	No	Levels	Fixed effects dummies	No	OLS
Khan and Luintel (2006)	Total factor productivity (based on value added)	R&D capital (business R&D capital and public R&D capital)	No	No	Levels	Fixed effects dummies	Time dummies included	- OLS - 2SLS - GMM-SYS
Lichtenberg and van Pottelsberghe de la Potterie (1998)	Total factor productivity (based on value added)	R&D capital (business R&D capital)	Yes	No	Levels	Fixed effects dummies	No	OLS
Mendi (2007)	Total factor productivity (based on value added)	R&D capital (business R&D capital)	Yes	No	Levels	Fixed effects dummies	No	- OLS - DOLS
Park (1995)	Labour productivity (based on value added)	R&D capital (business R&D capital and public R&D capital)	No	No	Growth (first differences)	-	-	- OLS - FGLS

Table B.6 R&D spillover mechanisms in macro studies used in the meta-analyses

Study	Spillovers from individual firms, industries or countries	Domestic: distinction between intrasectoral and intersectoral	International: distinction between intrasectoral, intersectoral and macro level	Transmission channel	Weights based on:
Ang and Madsen (2013)	From countries	Not applicable	Macro level	- Trade - Foreign direct investment - Technology flows - Geographical proximity - None specified	- Bilateral imports (LP*) - Bilateral exports - Inward foreign direct investment - Foreign patent flow (patent applications in the own county by residents of other countries - Geographical distance - Not applicable (no weighting scheme) in case of no transmission channel specified
del Barrio-Castro et al. (2002)	From countries	Not applicable	Macro level	Trade	Bilateral imports (CH*)
Coe and Helpman (1995)	From countries	Not applicable	Macro level	Trade	Bilateral imports (CH*)
Coe et al. (2009)	From countries	Not applicable	Macro level	- Trade - None specified (in a few estimates)	- Bilateral imports (CH* and LP*) - Unweighted average in case of no transmission channel specified
Edmond (2001)	From countries	Not applicable	Macro level	- Trade - None specified	- Bilateral imports (CH* and LP*) - Not applicable (no weighting scheme) in case of no transmission channel specified
Engelbrecht (1997)	From countries	Not applicable	Macro level	Trade	Bilateral imports (CH*)
Frantzen (2000)	From countries	Not applicable	Macro level	Trade	Bilateral imports (CH*)
Funk (2001)	From countries	Not applicable	Macro level	Trade	- Bilateral imports (CH*) - Random import weights (Keller) - Bilateral exports
Guellec and van Pottelsberghe de la Potterie (2004)	From countries	Not applicable	Macro level	Technological proximity	Degree of similarity between countries of the distribution of patents across technology classes (Jaffe’s method)
Kao et al. (1999)	From countries	Not applicable	Macro level	Trade	Bilateral imports

Table continues on next page.

Table B.6 (continued) R&D spillover mechanisms in macro studies used in the meta-analyses

Study	Spillovers from individual firms, industries or countries	Domestic: intrasectoral, intersectoral or combination of intrasectoral and intersectoral	International: intrasectoral, intersectoral, combination of intrasectoral and intersectoral or macro level	Transmission channel	Weights based on:
Keller (1998)	From countries	Not applicable	Macro level	- Trade - None specified	- Random import weights (Keller) - Not applicable (no weighting scheme) in case of no transmission channel specified
Khan and Luintel (2006)	From countries	Not applicable	Macro level	Technology flows	Joint patent applications of countries, as a measure for 'extent of successful R&D collaboration'
Lichtenberg and van Pottelsberghe de la Potterie (1998)	From countries	Not applicable	Macro level	Trade	Bilateral imports (CH* and LP*)
Mendi (2007)	From countries	Not applicable	Macro level	Trade	Bilateral imports (CH* and LP *)
Park (1995)	From countries	Not applicable	Macro level	Technological proximity	Degree of similarity between countries of the distribution of R&D across functional categories (e.g. electronics and chemicals)

* CH = Coe and Helpman approach: bilateral imports as share in total imports; LP = Lichtenberg and van Pottelsberghe de la Potterie approach: bilateral imports divided by value added.

RDC_{dom} = volume of domestic R&D capital at the macro level
RDC_{for} = volume of foreign R&D capital at the macro level
c = subscript denoting an individual country
t = subscript denoting an individual year

In equation (B.5) the parameter μ_1 is the output elasticity of domestic R&D capital and parameter μ_2 the output elasticity of foreign R&D capital. The output elasticity of foreign R&D capital measures international spillovers from R&D capital abroad. By writing this equation in first differences a growth equation results.

Output measures
Almost all studies at the macro level included in the meta-analyses use total factor productivity as output measure. The exception is Park (1995), who uses labour productivity. Assuming constant returns in labour input and physical capital ($\alpha + \beta = 1$), equation (B.5) can be rewritten in terms of total factor productivity:

$$\ln(TFP_{c,t}) = \ln(Y_{c,t}) - \alpha \ln(K_{c,t}) - \beta \ln(L_{c,t}) = \ln(A_{c,t}) + \mu_1 \ln(RDC_{dom_{c,t}}) + \mu_2 \ln(RDC_{for_{c,t}}) \qquad \text{(B.6)}$$

This is similar to the equation for total factor productivity at the meso level presented in the previous section (equation (B.4)). The inputs labour and physical capital partly include labour input and physical capital used for R&D activities. This means that the elasticity of domestic R&D capital in equation (B.6) represents extra returns on R&D capital, above the normal returns on labour and physical capital. These extra returns on domestic R&D capital can be considered largely as a result of domestic spillovers.

In the studies with total factor productivity as output measure the shares of labour income and capital income in value added have been used as weights for the production factors labour and physical capital. As described in the previous section on meso level studies, these weights represent output elasticities of labour input and physical capital in standard growth accounting analyses. In each study this is accompanied by assuming constant returns to scale with respect to labour input and physical capital as production factors.

G7 versus non-G7 countries and import shares
Several studies at the macro level use the Coe and Helpman (1995) framework with total factor productivity as output measurement. Part of this framework is a distinction between G7 countries (Canada, France, Germany, Italy, Japan, UK and USA) and non-G7 countries in estimates of the effect of domestic R&D capital. The G7 countries are larger than the other countries. In large countries R&D spillovers remain for a larger part within national boundaries, so it can be expected that in large countries domestic R&D capital has a larger effect on total factor productivity than in smaller countries. Furthermore, within the Coe and Helpman (1995) framework the import share is often used as interaction term in estimates of the effect of foreign R&D capital on total factor productivity. Countries with more openness towards foreign countries can be expected to have higher benefits from foreign R&D capital than countries that are relatively closed, which would result in a higher output elasticity of foreign R&D capital.

In the meta-analyses we include a distinction between G7 countries and non-G7 countries in the study characteristics. We do not include estimates of foreign R&D capital effects in which the output elasticity is dependent on the import share as an interaction term. The coefficients for the effect of foreign R&D capital express in that case elasticities divided by the import share. These coefficients can only be interpreted in terms of output elasticities if they are combined with values of the import share for different countries in different years.

Human capital
In several macro level studies human capital is included in part of the estimates: Engelbrecht (1997), Frantzen (2000), del Barrio-Castro et al. (2002), Ang and Madsen (2013), Khan and Luintel (2006) and Coe et al. (2009). This factor will be included as one of the study characteristics in the meta-analyses. Since indicators for human capital (generally measured by average years of education) and R&D capital are positively correlated, it is to be expected that including human capital in regressions has a negative influence on output elasticities found for R&D capital variables.

Input measurement
In all studies at the macro level R&D capital is used as input measure for R&D. In most studies a specific R&D deflator is used. In none of the studies a correction has been made for double counting of R&D. Guellec and van Pottelsberghe de la Potterie (2004), Khan and Luintel (2006) and Park (1995) include domestic public R&D capital besides domestic business R&D capital. Foreign R&D capital is limited to business R&D capital in these three studies. In the study by Ang and Madsen (2013) the calculation of R&D capital is based on the total of business and public R&D, for domestic as well as foreign R&D capital.

Estimation characteristics
A large majority of the estimates at the macro level are based on level variables. Park (1995) uses growth equations, formulated in first differences. Engelbrecht (1997), Frantzen (2000) and Guellec and van Pottelsberghe de la Potterie (2004) present both level estimates and growth estimates.

In all level estimates fixed effects are taken into account. In most studies fixed effects dummies are included. In a few studies mean group estimates are presented. In that case separate equations are estimated for the individual countries and the results for the countries together are calculated as averages of the results obtained for the individual countries. In the study by Ang and Madsen (2013) all estimates are mean group estimates. Coe et al. (2009) and Edmond (2001) present mean group estimates besides estimates with fixed effects dummies. Coe et al. (2009) show only a few mean group estimates, as part of a sensitivity check. In only a limited number of level estimates at the macro level time dummies are included and in none of the studies a time trend is included.

In the studies by Frantzen (2000) and Guellec and van Pottelsberghe de la Potterie (2004) the growth estimates are part of an error correction model. Frantzen (2000) follows the two step procedure developed by Engle and Granger (1987), in a similar way as Verspagen (1997) has done in his meso level study. Guellec and van Pottelsberghe de la Potterie (2004) use an error correction model in which the long-term equilibrium relation (in levels) and the short-term dynamics (in first differences) are estimated together (i.e. simultaneously). In both studies cointegration is confirmed. In almost all other macro level studies with level variables cointegration tests have been carried out. The study by Lichtenberg and van Pottelsberghe de la Potterie (1998) is the only one in which this issue does not receive attention. The general picture that can be derived from the various tests is that cointegration is confirmed.

Estimation methods
Ordinary Least Squares (OLS) and Dynamic Ordinary Least Squares (OLS) are often used as estimation methods at the macro level. Ang and Madsen (2013), del Barrio-Castro et al. (2002), Coe et al. (2009), Frantzen (2000), Funk (2001), Kao et al. (1999) and Mendi (1997) use DOLS for cointegration estimates in levels. Often different estimation methods are used to compare results. Coe and Helpman (1995) estimate cointegrated equations with OLS. Since in the presence of cointegration the distribution of OLS estimates is generally non-standard, no inference can be drawn about their significance. Therefore, Coe and Helpman (1995) do not present *t*-statistics. The same holds for OLS estimates in levels presented by Engelbrecht (1997), which extend Coe and Helpman (1995) with human capital as an explanatory factor. In a later extension by Coe et al. (2009) DOLS is used, a panel cointegration technique not yet available in the early 1990s. Another more advanced cointegration techniques is Fully Modified Ordinary Least Squares (FMOLS), used by Kao et al. (2009) and Funk (2001) as an alternative to DOLS. Similar to DOLS, FMOLS corrects for endogeneity and serial

correlation of the residuals, but is less preferred than DOLS in the just mentioned studies. DOLS outperforms FMOLS in parameter estimation and inference testing, as Funk (2001) notes, on the basis of an earlier comparative analyses of different cointegration estimation methods by Kao and Chiang (1998). In line with this, Kao et al. (2009) speak of superiority of DOLS over FMOLS estimates, also referring to Kao and Chiang (1998).

In growth estimates Engelbrecht (1997) uses Generalized Least Squares (GLS) to control for heteroskedasticity. He reports that OLS estimates of the growth equations resulted in non-normally distributed residuals. Guellec and van Pottelsberghe de la Potterie (2004) apply Seemingly Unrelated Regression (SUR) in level estimates and in part of the error correction model estimates, to correct for contemporaneous correlation of the error term across countries. In other error correction model estimates they use Three-Stage Least Squares (3SLS) to correct for the presence of a lagged endogenous variable among the explanatory variables, for which the two year lagged value of that variable is used as instrument. This controls for potential simultaneity bias. Park (1995) uses Feasible Generalized Least Squares (FGLS) for random effects estimates of growth equations, which he presents besides growth equations with fixed effects and growth equations without fixed or random effects (all estimated with OLS).

Khan and Luintel (2006) use Two-Stage Least Squares (2SLS) in a part of the estimates by using lagged values as instruments for most regressors, as a control for endogeneity. They prefer System Generalized Method of Moments (GMM-SYS) as estimation method, in order to address three issues: 1) potential endogeneity of the explanatory variables (they state: productivity and some of its determinants may be jointly determined), 2) ‘inertia’, i.e. persistent data combined with moderately short time series and 3) possible measurement errors. GMM-SYS estimates a system of equations in levels and first differences. Lagged values of explanatory variables in first differences are used as instruments for explanatory variables in the level equation and lagged values of variables in levels are used as instruments for explanatory variables in the first differences equation. An interesting feature of Khan and Luintel (2006) is that they estimate a heterogeneous panel in which the effects of the explanatory variables are estimated with interaction terms representing mean values of the various explanatory variables. As a consequence, the estimated output elasticities for the R&D capital variables vary between countries, dependent on the mean values of the explanatory variables. In the meta-analyses output elasticities for the Netherlands, the USA and the average for all 16 OECD countries in the sample of Khan and Luintel (2006) are included, based on GMM-SYS estimates.

R&D spillovers
All macro level studies contain spillover effects of outside R&D. This concerns the effect of R&D capital of foreign countries on domestic output. Weights are mostly based on trade as transmission mechanism, as Table B.6 shows. This has its origin in the influential Coe and Helpman (1995) study, who weighted foreign R&D capital on the basis of bilateral import weights. Technological proximity is assumed as transmission mechanism in two studies: Guellec and van Pottelsberghe de la Potterie (2004) and Park (1995).

Appendix C Results of meta-analyses for output elasticities of own R&D at the micro and meso level

Table C.1 Estimation results of meta-analysis for output elasticities of own R&D, micro studies only

	OLS, basic		**OLS, with equal weights for each study**		**Random effects, basic**		**Random effects, with equal weights for each study**	
	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statisic	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic
Constant	0.034	1.17	0.068	2.54	0.040	1.39	0.071	2.82
Input measurement (reference: R&D capital, 10 to 20% depreciation rate of R&D capital, no specific R&D deflator, no correction for double counting of R&D)								
R&D expenditure	0.000	0.00	0.054	1.71	–0.003	–0.16	0.034	1.79
Depreciation rate of R&D capital:								
- less than 10%	0.022	1.27	0.001	0.07	0.014	0.85	–0.003	–0.22
- 20% or more	–0.008	–0.86	–0.008	–0.69	–0.004	–0.48	0.004	0.34
Specific R&D deflator	0.032	2.10	0.008	0.65	0.019	1.50	0.007	0.70
Correction for double counting of R&D	0.043	4.37	0.047	3.41	0.045	4.72	0.042	3.92
Output measurement (reference: labour productivity or capital productivity)								
Value added	–0.014	–1.32	–0.022	–0.96	–0.017	–1.66	–0.012	–0.84
Sales or gross production	–0.047	–3.09	–0.026	–1.11	–0.048	–3.37	–0.040	–2.10
Total factor productivity	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Partial productivity	–0.005	–0.58	–0.026	–0.81	0.012	1.12	0.024	1.42
Production function characteristics (reference: human capital not implemented in regression, in case of sales or gross output as output measure (directly or within a productivity measure) intermediate inputs not taken into account, constant returns to scale in factor inputs imposed, besides private R&D no public R&D taken into account, international R&D spillovers not taken into account domestic intrasectoral and intersectoral R&D spillovers not taken into account)								
Human capital in regression	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
In case of sales or gross output as output measure (directly or within a productivity measure): intermediate inputs taken into account	–0.049	–2.57	–0.166	–1.80	–0.041	–3.53	–0.092	–1.76
Constant returns to scale not imposed	–0.048	–9.23	–0.038	–2.68	–0.043	–6.21	–0.039	–3.21
Besides private R&D also public R&D taken into account	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

Table continues on next page.

Table C.1 (continued) Estimation results of meta-analysis for output elasticities of own R&D, micro studies only

	OLS, basic		**OLS, with equal weights for each study**		**Random effects, basic**		**Random effects, with equal weights for each study**	
	Coefficient	*t* statistic	Coefficient	*t* statistic	Coefficient	*t* statistic	Coefficient	*t* statistic
Production function characteristics (continued)								
International R&D spillovers taken into account	0.197	16.48	0.209	9.46	0.198	15.33	0.191	13.51
Domestic intrasectoral and/or intersectoral R&D spillovers taken into account	0.039	2.29	–0.005	–0.29	0.037	2.61	0.006	0.42
Estimation characteristics (reference: panel, fixed effects, homogeneity of output elasticity, estimation in levels, lagged R&D input, no time dummies or time trend included in regression)								
Cross-sectional or totals estimates	0.071	2.68	0.047	2.71	0.071	2.80	0.042	2.74
Random effects (level or growth estimate)	0.098	3.61	0.103	3.13	0.120	4.86	0.124	6.44
Mean Group Estimate / heterogeneous panel estimate (level estimate)	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Growth estimate	0.067	1.76	0.060	2.64	0.041	0.95	0.004	0.12
In case of growth estimate: long differences	0.005	0.37	0.002	0.17	0.013	1.02	0.005	0.35
Unlagged R&D input in case of level estimate	–0.020	–1.28	–0.017	–1.23	–0.015	–1.25	–0.016	–1.88
Unlagged R&D input in case of growth estimate	0.051	4.51	0.065	3.28	0.058	4.35	0.083	5.50
Time dummies or time trend included in level estimate	0.064	4.67	0.040	2.47	0.058	4.39	0.043	3.48
Time dummies or time trend included in growth estimate	0.007	0.27	–0.029	–0.79	0.024	0.77	0.035	1.25
Estimation method (reference: Ordinary Least Squares (OLS))*								
Dynamic OLS (DOLS)	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Engle-Granger-Yoo three step procedure	0.034	2.17	0.012	1.14	0.033	2.21	0.016	1.58
Difference Generalized Method of Moments (GMM-DIF)	–0.131	–18.44	–0.128	–7.64	–0.125	–7.46	–0.148	–6.45
Two-Stage Least Squares (2SLS)	0.021	1.80	0.018	1.71	0.015	1.63	0.011	1.72
Other (residual category): Feasible Generalized Least Squares (FGLS), Weighted Lest Squares (WLS) or Seemingly Unrelated Regression (SUR)	–0.058	–4.56	–0.069	–2.60	–0.076	–7.83	–0.094	–6.42
Sectors (reference: no distinction)								
High tech	0.041	3.22	0.058	3.86	0.029	2.65	0.042	3.53
Medium tech	0.004	0.39	0.008	0.68	–0.001	–0.12	0.005	0.50
Low tech	–0.024	–1.15	–0.034	–1.42	–0.031	–1.51	–0.033	–1.50
Medium and low tech combined	–0.061	–3.95	–0.075	–2.73	–0.068	–4.93	–0.077	–3.29
Number of observations	377		377		375		375	
R^2	0.610		0.653		0.833		0.853	

Table continues on next page.

Table C.1 (continued) Estimation results of meta-analysis for output elasticities of own R&D, micro studies only

	OLS, basic		**OLS, with equal weights for each study**		**Random effects, basic**		**Random effects, with equal weights for each study**	
Additional estimate with the standard error of the output elasticity included as explanatory variable, in the context of possible publication bias (only estimation results for the standard error and the constant are shown, together with the R^2 and the number of observations):								
	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic
Standard error of coefficient	–0.053	–0.51	0.058	0.73	0.007	0.01	0.717	1.19
Constant	0.035	1.29	0.067	2.54	0.040	1.65	0.053	2.00
Number of observations	375**		375**		375		375	
R^2	0.612		0.659		0.833		0.859	

* No Fully Modified OLS (FMOLS), System Generalized Method of Moments (GMM-SYS), Three-Stage Least Squares (3SLS) and Generalized Least Squares (GLS) estimates available in observations at the micro level.

** Limited slightly by availability of standard errors for coefficients. Therefore, the number of observations is the same here as in the case of random effects estimates.

Notes (general):

- The *t* statistics are based on cluster robust standard errors.
- The standard errors of the observations used in the random effects estimates are constrained to a minimum value of 0.002. This has hardly any effect on the results.

Table C.2 Estimation results of meta-analysis for output elasticities of own R&D, meso studies only

	OLS, basic		**OLS, with equal weights for each study**		**Random effects, basic**		**Random effects, with equal weights for each study**	
	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic
Constant	0.095	4.26	0.127	4.75	0.114	4.78	0.100	5.13
Effect of G7/non-G7 at meso level (reference: G7 and non-G7 countries combined)								
G7 countries or country, meso level	–0.074	–1.44	–0.101	–3.01	–0.044	–1.04	–0.124	–3.09
Non-G7 countries or country, meso level	–0.073	–1.44	–0.079	–2.30	–0.037	–0.97	–0.059	–1.71
Input measurement (reference: R&D capital, 10 to 20% depreciation rate of R&D capital, no specific R&D deflator, no correction for double counting of R&D)								
R&D expenditure	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Depreciation rate of R&D capital:								
- less than 10%	Collinearity; variable coincides with ‘Total factor productivity’*							
- 20% or more	0.097	2.46	0.117	2.72	0.062	1.66	0.073	1.79
Specific R&D deflator	0.094	3.69	0.052	1.84	0.100	5.76	0.068	2.92
Correction for double counting of R&D	0.000	0.03	0.000	0.02	0.001	0.25	0.001	0.08
Output measurement (reference: labour productivity**)								
Value added	Collinearity; variable coincides with ‘Two-Stage or Three-Stage Least Squares’***							
Sales or gross production	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Total factor productivity	0.012	0.43	–0.023	–0.80	0.041	1.52	0.021	0.82
Partial productivity	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Production function characteristics (reference: human capital not implemented in regression, in case of sales or gross output as output measure (directly or within a productivity measure) intermediate inputs not taken into account, constant returns to scale in factor inputs imposed, besides private R&D no public R&D taken into account, international R&D spillovers taken into account, domestic intersectoral R&D spillovers taken into account)								
Human capital in regression	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
In case of sales or gross output as output measure (directly or within a productivity measure): intermediate inputs taken into account	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

Table continues on next page.

Table C.2 (continued) Estimation results of meta-analysis for output elasticities of own R&D, meso studies only

	OLS, basic		**OLS, with equal weights for each study**		**Random effects, basic**		**Random effects, with equal weights for each study**	
	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic
Production function characteristics (continued)								
Constant returns to scale not imposed	Collinearity; reverse ‘Constant returns to scale imposed’ coincides with ‘Total factor productivity’*							
Besides private R&D also public R&D taken into account	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
International R&D spillovers not taken into account	–0.002	–0.12	–0.002	–0.22	–0.002	–0.08	–0.002	–0.18
Domestic intersectoral R&D spillovers not taken into account	0.015	1.01	0.001	0.17	0.026	1.22	0.005	0.44
Estimation characteristics (reference: panel, fixed effects, homogeneity of output elasticity, estimation in levels, lagged R&D input, no time dummies or time trend included in regression)								
Cross-sectional or totals estimates	–0.031	–1.27	–0.058	–2.32	–0.007	–0.44	–0.028	–1.38
Random effects (level or growth estimate****)	–0.010	–0.27	–0.038	–0.96	–0.001	–0.04	–0.024	–0.73
Mean Group Estimate / heterogeneous panel estimate (level estimate)	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Growth estimate	0.003	0.11	–0.052	–1.78	0.021	1.32	–0.026	–1.00
In case of growth estimate: long differences	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Unlagged R&D input in case of level estimate	0.039	0.69	0.020	0.39	0.018	0.45	0.024	0.55
Unlagged R&D input in case of growth estimate	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Time dummies or time trend included in level estimate	–0.060	–0.99	–0.033	–0.58	–0.047	–1.00	–0.032	–0.66
Time dummies or time trend included in growth estimate	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Estimation method (reference: Ordinary Least Squares (OLS))*****								
Dynamic OLS (DOLS)	–0.016	–0.76	0.004	0.20	–0.009	–0.65	0.009	0.57
Fully Modified OLS (FMOLS) or Engle-Granger-Yoo three step procedure	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Difference Generalized Method of Moments (GMM-DIF) or System Generalized Method of Moments (GMM-SYS)	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Three-Stage Least Squares (3SLS)	0.036	0.63	0.033	0.62	0.011	0.24	0.064	1.29
Other (residual category): Feasible Generalized Least Squares (FGLS)	Collinearity; variable coincides with ‘Random effects’******							
Sectors (reference: no distinction)								
High tech	0.018	0.76	–0.001	–0.04	0.036	2.27	0.019	0.79
Medium tech	–0.018	–1.07	–0.016	–0.87	–0.002	–0.16	–0.013	–0.76
Low tech	–0.041	–2.70	–0.040	–2.26	–0.033	–3.69	–0.041	–2.64
Medium and low tech combined	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

Table continues on next page.

Table C.2 (continued) Estimation results of meta-analysis for output elasticities of own R&D, meso studies only

	OLS, basic		**OLS, with equal weights for each study**		**Random effects, basic**		**Random effects, with equal weights for each study**	
Number of observations R^2	121 0.642		121 0.775		121 0.925		121 0.920	
Additional estimate with the standard error of the output elasticity included as explanatory variable, in the context of possible publication bias (only estimation results for the standard error and the constant are shown, together with the R^2 and the number of observations):								
	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic
Standard error of coefficient	–1.184	–3.80	–1.626	–5.43	–0.742	–2.48	–0.175	–4.35
Constant	0.099	4.89	0.128	5.35	0.131	5.43	0.161	8.26
Number of observations R^2	121 0.722		121 0.831		121 0.929		121 0.930	

* Perfect collinearity, caused by coincidence of characteristics in the studies by López-Pueyo et al. (2008) and Braconier and Sjöholm (1998).

** No capital productivity available in observations at the meso level. Therefore, labour productivity is not combined with capital productivity on the reference path in this analysis at the meso level.

*** Perfect collinearity, caused by coincidence of characteristics in the study by Verspagen (1995).

**** In case of random effects estimates in the meta-analysis only random effects level estimates available in observations at the meso level.

***** No Two-Stage Least Squares (2SLS), Generalized Least Squares (GLS), Weighted Least Squares (WLS) and Seemingly Unrelated Regression (SUR) estimates available in observations at the meso level.

****** Perfect collinearity; caused by coincidence of characteristics in the study by Ortega-Argilés et al. (2010). The estimation characteristic 'Random effects' in this study implies Feasible Generalized Least Squares (FGLS) as estimation method.

Notes:

- The *t* statistics are based on 'regular' robust standard errors. As mentioned in Section 3, cluster robust standard errors are not used here, because the relatively low number of clusters (studies) in the analysis at the meso level (as a matter of fact: 7) can lead to bias in the calculation of robust standard errors (Ringquist, 2013, p. 199).
- The standard errors of the observations used in the random effects estimates are constrained to a minimum value of 0.002. This has hardly any effect on the results.

Appendix D Supplementary meta-analysis regressions for output elasticities of outside R&D, for the purpose of sensitivity checks

Table D.1 Estimation results of meta-analysis for output elasticities of outside R&D, with control for possible publication bias; all data levels

	OLS, basic		**OLS, with equal weights for each study**		**Random effects, basic**		**Random effects, with equal weights for each study**	
	Coefficient	*t* statistic	Coefficient	*t* statistic	Coefficient	*t* statistic	Coefficient	*t* statistic
Constant	0.291	2.88	0.335	2.45	0.270	2.35	0.355	2.95
Control for possible publication bias								
Standard error of the coefficient	1.022	6.35	1.460	4.76	1.331	3.36	1.534	4.17
Type of R&D spillovers (reference: international, macro level)								
Domestic, from individual firms								
- Intrasectoral	–0.133	–1.55	–0.126	–1.35	–0.135	–1.55	–0.169	–2.13
- Intersectoral	–0.479	–5.57	–0.546	–5.29	–0.444	–4.78	–0.492	–6.13
- Intrasectoral and intersectoral combined	–0.216	–2.26	0.013	0.06	–0.236	–2.86	0.002	0.01
Domestic, from industries								
- Intrasectoral	Collinearity; variable coincides with 'Value added'*							
- Intersectoral	–0.010	–0.09	–0.223	–1.79	–0.005	–0.04	–0.175	–1.48
- Intrasectoral and intersectoral combined	0.302	2.52	0.528	2.29	0.367	2.81	0.617	2.52
International, from individual firms or industries								
- Intrasectoral	0.035	0.64	0.038	0.62	0.027	0.52	0.026	0.46
- Intersectoral	0.042	0.82	–0.017	–0.24	0.035	0.61	–0.008	–0.12
- Intrasectoral and intersectoral combined	0.013	0.15	–0.161	–1.35	0.026	0.28	–0.091	–0.79
Effect of G7 (reference: non-G7 countries or country)								
G7 countries or country, domestic spillovers	0.101	0.59	–0.242	–0.97	0.177	0.92	–0.276	–0.99
G7 and non-G7 countries combined, domestic spillovers	–0.042	–1.10	–0.057	–0.74	–0.032	–0.89	–0.041	–0.77
G7 countries or country, international spillovers	–0.164	–1.47	–0.308	–1.75	–0.205	–1.46	–0.357	–2.53
G7 and non-G7 countries combined, international spillovers	–0.046	–0.60	–0.075	–0.68	–0.052	–0.64	–0.098	–1.21
Transmission channel for spillovers (reference: trade)								
Technological proximity	0.296	3.70	0.314	3.39	0.288	3.31	0.270	2.84
Technology flows	–0.141	–2.24	–0.131	–1.56	–0.140	–2.12	–0.170	–2.05
Technological proximity and trade combined	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Technology flows and trade combined	0.162	2.55	0.299	4.38	0.137	2.80	0.224	4.40
Geographical proximity	0.156	11.68	0.155	11.79	0.154	11.59	0.151	11.80
Foreign direct investment	0.008	0.66	0.021	1.63	0.017	1.21	0.020	1.57
None specified	–0.053	–0.83	–0.002	–0.05	–0.009	–0.16	0.022	0.61

Table continues on next page.

Table D.1 (continued) Estimation results of meta-analysis for output elasticities of outside R&D, with control for possible publication bias; all data levels

	OLS, basic		**OLS, with equal weights for each study**		**Random effects, basic**		**Random effects, with equal weights for each study**	
	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic
Private or public outside R&D, at macro level (reference: private outside R&D)								
Public outside R&D	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Total outside R&D (i.e. private and public outside R&D)	Collinearity; variable coincides with 'Mean group estimate'**							
Input measurement of outside R&D (reference: R&D capital, 10 to 20% depreciation rate of R&D capital, no specific R&D deflator)								
R&D expenditure	Collinearity; variable coincides with 'Value added'*							
Depreciation rate of R&D capital:								
- less than 10%	–0.125	–2.27	–0.130	–2.45	–0.104	–1.72	–0.131	–2.93
- 20% or more	Collinearity; variable coincides with 'Mean group estimate'**							
Specific R&D deflator	–0.008	–0.18	–0.032	–0.60	–0.019	–0.37	–0.038	–0.72
Output measurement (reference: total factor productivity)								
Value added	0.367	1.33	0.654	1.89	0.191	0.74	0.529	1.49
Sales or gross production	0.116	0.81	0.141	1.07	–0.025	–0.17	0.094	0.79
Labour productivity***	0.085	1.19	0.088	1.03	0.081	1.02	0.119	1.66
Partial productivity	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Production function characteristics (reference: human capital not implemented in regression, in case of sales or gross output as output measure (directly or within a productivity measure) intermediate inputs not taken into account, constant returns to scale in factor inputs imposed, in case of domestic spillovers foreign R&D spillovers taken into account, no correction for double counting of own R&D)								
Human capital in regression	0.007	0.14	0.015	0.29	–0.004	–0.08	0.003	0.05
In case of sales or gross output as output measure (directly or within a productivity measure): intermediate inputs taken into account	0.084	1.26	0.117	4.08	0.084	0.40	0.200	2.24
Constant returns to scale not imposed	–0.296	–2.45	–0.278	–2.07	–0.250	–1.85	–0.295	–2.61
In case of domestic spillovers foreign R&D spillovers not taken into account	0.013	0.19	0.041	0.99	–0.003	–0.03	0.089	2.53
In case of private outside R&D: also outside public R&D taken into account	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
In case of public outside R&D: also outside private R&D taken into account	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Correction for double counting of own R&D	–0.087	–0.87	–0.117	–1.03	–0.113	–1.11	–0.136	–1.33

Table continues on next page.

Table D.1 (continued) Estimation results of meta-analysis for output elasticities of outside R&D, with control for possible publication bias; all data levels

	OLS, basic		OLS, with equal weights for each study		Random effects, basic		Random effects, with equal weights for each study	
	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic
Estimation characteristics (reference: panel, fixed effects, homogeneity of output elasticity, estimation in levels, lagged R&D input, no time dummies or time trend included in regression)****								
Cross-sectional or totals estimates	–0.291	–2.35	–0.308	–2.55	–0.274	–2.14	–0.266	–2.38
Random effects (level or growth estimate)	0.154	4.06	0.119	2.44	0.129	2.96	0.100	2.62
Mean Group Estimate (level estimate)	–0.101	–2.67	–0.075	–2.48	–0.075	–1.43	–0.075	–3.41
Growth estimate	–0.165	–3.13	–0.147	–2.04	–0.151	–2.92	–0.130	–2.00
In case of growth estimate: long differences	–0.434	–4.62	–0.409	–4.03	–0.410	–2.85	–0.394	–3.31
Unlagged R&D input in case of level estimate	–0.044	–0.91	–0.051	–1.00	–0.033	–0.76	–0.064	–1.08
Unlagged R&D input in case of growth estimate	0.063	1.01	–0.041	–0.46	0.186	2.41	0.083	0.89
Time dummies or time trend included in level estimate	–0.096	–1.14	–0.163	–1.51	–0.079	–0.75	–0.119	–1.15
Time dummies or time trend included in growth estimate	–0.255	–2.88	–0.296	–2.46	–0.260	–2.48	–0.293	–2.59
Estimation method (reference: Ordinary Least Squares (OLS))*****								
Dynamic OLS (DOLS)	–0.027	–0.88	–0.061	–1.05	–0.027	–0.79	–0.051	–0.98
Fully Modified OLS (FMOLS) or Engle-Granger-Yoo three step procedure	0.059	1.21	–0.021	–0.53	0.048	1.12	–0.022	–0.64
Difference Generalized Method of Moments (GMM-DIF)	0.242	17.78	0.231	3.40	0.174	4.15	0.169	2.15
Two-Stage or Three-Stage Least Squares (2SLS or 3SLS)	–0.018	–0.66	–0.015	–0.74	–0.005	–0.18	–0.000	–0.02
Other (residual category): Feasible Generalized Least Squares (FGLS) or Seemingly Unrelated Regression (SUR)	–0.075	–2.42	–0.073	–2.27	–0.061	–2.04	–0.060	–2.45
Sectors (reference: no distinction)								
High tech	0.060	1.05	0.070	0.99	–0.021	–0.40	–0.029	–0.44
Medium tech	0.018	0.52	0.015	0.35	0.031	0.50	0.022	0.32
Low tech	–0.069	–1.48	–0.072	–1.27	–0.095	–1.77	–0.105	–1.89
Medium and low tech combined	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Number of observations	358		358		358		358	
R^2	0.462		0.607		0.737		0.762	

* Perfect collinearity, caused by coincidence of characteristics in the study by Rogers (2010).
** Perfect collinearity, caused by coincidence of characteristics in the study by Ang and Madsen (2013).
*** No capital productivity available in observations for output elasticities of outside R&D.
**** No heterogeneous panel estimate available in observations for which standard errors of the coefficients are known (in order to control for possible publication bias).

Notes continue on next page.

***** No System Generalized Method of Moments (GMM-SYS) estimate available in the observations for which standard errors of the coefficients are known (in order to control for possible publication bias) and no Generalized Least Squares (GLS) and Weighted Least Squares (WLS) estimates available in the observations for output elasticities of outside R&D.

Notes (general):
- The *t* statistics are based on cluster robust standard errors.
- The standard errors of the observations used in the random effects estimates are constrained to a minimum value of 0.002. This has hardly any effect on the results.

Table D.2 Estimation results of meta-analysis for output elasticities of outside R&D at all data levels, without control for possible publication bias; *only explanatory variables directly related to spillovers included*

	OLS, basic		**OLS, with equal weights for each study**		**Random effects, basic**		**Random effects, with equal weights for each study**	
	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic
Constant	0.122	3.43	0.083	1.39	0.170	3.56	0.144	2.33
Type of R&D spillovers (reference: international, macro level)								
Domestic, from individual firms								
- Intrasectoral	–0.084	–1.02	–0.022	–0.16	–0.137	–1.82	–0.108	–0.93
- Intersectoral	–0.258	–3.13	–0.197	–1.41	–0.366	–4.88	–0.338	–2.91
- Intrasectoral and intersectoral combined	–0.048	0.30	0.529	2.06	–0.075	–0.60	0.305	1.33
Domestic, from industries								
- Intrasectoral	–0.242	–1.15	0.151	0.78	–0.349	–1.85	0.053	0.27
- Intersectoral	0.214	2.07	0.063	0.79	0.108	1.22	–0.015	–0.21
- Intrasectoral and intersectoral combined	0.171	0.82	0.339	1.26	0.101	0.49	0.283	1.05
International, from individual firms or industries								
- Intrasectoral	0.001	0.02	–0.014	–0.27	–0.006	–0.12	–0.013	–0.27
- Intersectoral	0.117	3.18	0.117	3.67	0.088	2.99	0.079	2.88
- Intrasectoral and intersectoral combined	0.142	1.45	0.057	0.78	0.058	0.77	–0.009	–0.15
Effect of G7 (reference: non-G7 countries or country)								
G7 countries or country, domestic spillovers	0.048	0.28	–0.276	–1.28	0.064	0.41	–0.255	–1.20
G7 and non-G7 countries combined, domestic spillovers	–0.128	–2.70	–0.111	–1.55	–0.111	–2.49	–0.070	–1.61
G7 countries or country, international spillovers	–0.078	–1.10	–0.064	–1.00	–0.167	–1.87	–0.160	–2.02
G7 and non-G7 countries combined, international spillovers	0.008	0.23	0.042	0.75	–0.038	–0.88	–0.016	–0.28
Transmission channel for spillovers (reference: trade)								
Technological proximity	0.082	2.36	0.041	0.59	0.069	1.86	0.026	0.34
Technology flows	–0.010	–0.09	0.039	0.35	–0.006	–0.05	0.000	0.00

Table continues on next page.

Table D.2 (continued) Estimation results of meta-analysis for output elasticities of outside R&D at all data levels; *only explanatory variables directly related to spillovers included*

	OLS, basic		OLS, with equal weights for each study		Random effects, basic		Random effects, with equal weights for each study	
	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic
Transmission channel for spillovers, continued								
Technological proximity and trade combined	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Technology flows and trade combined	–0.137	–1.50	–0.006	–0.10	–0.081	–1.19	0.012	0.30
Geographical proximity	0.171	7.75	0.176	5.90	0.169	7.59	0.173	6.76
Foreign direct investment	–0.008	–0.35	–0.003	–0.10	–0.010	–0.46	–0.006	–0.24
None specified	0.076	0.81	0.046	0.78	0.119	1.25	0.062	1.28
Number of observations	387		387		358		358	
R^2	0.199		0.177		0.536		0.456	

Notes (general):
- The *t* statistics are based on cluster robust standard errors.
- The standard errors of the observations used in the random effects estimates are constrained to a minimum value of 0.002. This has hardly any effect on the results.

Table D.3 Estimation results of meta-analysis for output elasticities of outside R&D at all data levels, with control for possible publication bias; *only explanatory variables directly related to spillovers included*

	OLS, basic		OLS, with equal weights for each study		Random effects, basic		Random effects, with equal weights for each study	
	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic
Constant	0.145	2.72	0.076	0.99	0.145	3.37	0.100	1.72
Control for possible publication bias								
Standard error of the coefficient	0.865	3.58	1.366	5.26	1.079	3.08	1.458	4.38
Type of R&D spillovers (reference: international, macro level)								
Domestic, from individual firms								
- Intrasectoral	–0.122	–1.31	–0.080	–0.50	–0.145	–1.77	–0.136	–1.06
- Intersectoral	–0.442	–4.14	–0.484	–2.61	–0.433	–4.89	–0.444	–3.23
- Intrasectoral and intersectoral combined	–0.068	–0.43	0.334	1.36	–0.133	–1.01	0.266	1.02

Table continues on next page.

Table D.3 (continued) Estimation results of meta-analysis for output elasticities of outside R&D, with control for possible publication bias; all data levels; *only explanatory variables directly related to spillovers included*

	OLS, basic		**OLS, with equal weights for each study**		**Random effects, basic**		**Random effects, with equal weights for each study**	
	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic	Coeffi-cient	*t* statistic
Type of R&D spillovers, continued								
Domestic, from industries								
- Intrasectoral	–0.229	–1.01	0.205	1.00	–0.323	–1.59	0.143	0.60
- Intersectoral	0.052	0.51	–0.130	–1.34	0.023	0.23	–0.146	–1.52
- Intrasectoral and intersectoral combined	0.094	0.41	0.317	1.18	0.073	0.34	0.320	1.08
International, from individual firms or industries								
- Intrasectoral	–0.016	–0.32	–0.017	–0.37	–0.015	–0.37	–0.015	–0.38
- Intersectoral	0.039	1.22	–0.030	–0.48	0.039	1.53	–0.007	–0.12
- Intrasectoral and intersectoral combined	0.016	0.19	–0.096	–1.15	–0.009	–0.11	–0.111	–1.45
Effect of G7 (reference: non-G7 countries or country)								
G7 countries or country, domestic spillovers	0.056	0.34	–0.297	–1.33	0.083	0.51	–0.299	–1.19
G7 and non-G7 countries combined, domestic spillovers	–0.108	–2.19	–0.073	–1.11	–0.092	–1.89	–0.042	–0.85
G7 countries or country, international spillovers	–0.152	–1.50	–0.226	–1.79	–0.212	–2.02	–0.295	–2.55
G7 and non-G7 countries combined, international spillovers	–0.025	–0.48	0.019	0.24	–0.039	–0.92	–0.013	–0.22
Transmission channel for spillovers (reference: trade)								
Technological proximity	0.033	0.79	–0.001	–0.01	0.308	0.70	–0.002	–0.03
Technology flows	0.005	0.04	0.009	0.07	–0.009	–0.08	–0.001	–0.01
Technological proximity and trade combined	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Technology flows and trade combined	–0.034	–0.43	0.136	1.70	–0.014	–0.19	0.125	2.02
Geographical proximity	0.149	6.60	0.155	7.51	0.154	7.88	0.160	8.27
Foreign direct investment	–0.003	–0.14	0.019	0.91	0.009	0.44	0.026	1.49
None specified	0.031	0.28	0.016	0.31	0.095	1.02	0.056	1.22
Number of observations		358*		358*		358		358
R^2		0.259		0.350		0.562		0.528

* Limited by availability of standard errors for coefficients. Therefore, the number of observations is the same here as in the case of random effects estimates.

Notes (general):
- The *t* statistics are based on cluster robust standard errors.
- The standard errors of the observations used in the random effects estimates are constrained to a minimum value of 0.002. This has hardly any effect on the results.

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